

CR-119935

Final Report

**PROPELLANT QUANTITY
GAUGING SYSTEM
UNDER ZERO G**

August 17, 1971

NASA George C. Marshall Space Center

Contract NAS 8-26116



FACILITY FORM 602

N71-36104
(ACCESSION NUMBER)

79
(PAGES)

CR-119935
(NASA CR OR TMX OR AD NUMBER)

G3 (THRU)
G3 (CODE)
27 (CATEGORY)



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1.0 INTRODUCTION

This is the final report summarizing the results of the study "Propellant Quantity Gauging System Under Zero-G". The study was performed for NASA George C. Marshall Space Center under Contract NAS 8-26116 between June, 1970 and July, 1971.

The objective of this study was to evaluate candidate propellant gauging systems suitable for use on the Space Shuttle Vehicle with the exception of the Radio Frequency gauge which was specifically excluded by NASA.

The results indicate that shuttle tanks with extensive surface tension screens are virtually impossible to gauge by conventional means. Unless some propellant settling technique is used, the only means of gauging such tanks appears to be using Nuclear Gauging techniques for LH₂ and the TRW RIGS for LOX.

Recommendations for future development of the gauging systems are included in this report.

The report is presented in four sections:

Section 2 is a summary of the program.

Section 3 is a brief technical discussion of various gauging systems.

Section 4 gives conclusions and recommendations for continuation of work started under this program.

2.0 SUMMARY

The study of various zero-g propellant gauging systems as they apply to the Space Shuttle Vehicle, resulted in the following findings:

- Gauging of all tanks becomes significantly easier if some form of propellant settling is employed.
- The gauging system design will be profoundly affected by the internal structure of the tank.
- The Shuttle Vehicle, most likely will employ tanks with extensive surface tension screens.
- Tanks employing extensive surface tension screens (so that the interior of the tank is subdivided into small compartments) are virtually impossible to gauge by conventional means. Unless some propellant settling technique is used, the only means of gauging such tanks appears to be using Nuclear Gauging techniques and for LOX TRW's RIGS.

2.1 PROPELLANT SETTLING

To simplify propellant gauging, (regardless of what types of gauging may be employed), a means for settling the propellant is very desirable. For instance, a Nuclear Gauge (such as currently being developed by TRW for the Air Force Rocket Propulsion Center at Edwards, California) which requires the use of 18 source-detector pairs to gauge propellant in true zero-g condition could operate with the same accuracy using on the order of 5 source-detector pairs when the propellant is settled in a known configuration.

As a result of the study a propellant settling scheme using a "sprinkler" was derived and analysis performed to date indicated that such a system could be made to operate with a minimum power requirement and complication of the tank design. A proposal for tests of the sprinkler system TRW No. 16878.002, "Destratification Test in Zero-G" was submitted to NASA/MSFC on April 8, 1971. The proposed program includes system tests and a feasibility demonstration in a small, ~2 gallon tank, using simulated propellants. The tests are to be conducted by free-floating the test tank using a KC-135 zero-g aircraft. Successful completion of this program would be followed by using approximately 1/4 scale Shuttle Vehicle tank with LOX in a simulated zero-g environment such as a high altitude rocket flight.

2.2 NUCLEAR AND LIQUID LEVEL GAUGING

The gauging of LH_2 under zero-g is a difficult task. The only system that appears capable of performing the task under all conditions is the Nuclear Gauge (unless the RF gauge, which has been excluded from TRW's study, can be proven to work also).

The Nuclear Gauge basically consists of radioisotope sources located on one side of the tank and detectors on the other. The gamma radiation emitted from the sources penetrates the tank walls, is partially absorbed by the propellant, and emerges on the other side. The radiation that penetrates the tank is detected by the detectors and, in turn is related to the propellant quantity. The nuclear gauge inherently measures the mass of propellant and can be built completely external to the tank. The gauge will work equally well under zero- and one-g conditions.

If LH_2 is settled or destratified, level measurements can be employed such as capacitance or TRW's Ultrasonic Liquid Level Detector (in addition to the RF and Nuclear Gauges). The Ultrasonic Liquid Level Probe appears particularly attractive because of its simplicity and the characteristic that it measures the mass of the liquid in contact with the probe. Since the Ultrasonic Liquid Level Probe is simple to design and construct, a very modest development effort would be required to fabricate and test a prototype unit. A program for development of the Ultrasonic Liquid Level Detector has been submitted to NASA/MSFC in the previously mentioned proposal "Destratification Test in Zero-G."

The Nuclear Gauge, which is very well suited for gauging LH_2 becomes less attractive when used with LOX in large tanks. The reason is that gamma radiation emitted from the source (assuming Co-60) can penetrate only on the order of 5 feet of LOX. In tanks where the tank dimensions are greater than 5 feet, the sources have to be placed inside the tank to decrease the source-detector distance. It is not practical to use Nuclear Gauging for LOX tanks larger than approximately 10 feet in diameter (at least by the gauging system that is being designed by TRW for Air Force Rocket Propulsion Center).*

*The practical tank size may be increased somewhat by use of sources which emit higher energy gamma rays than Co-60 (1.17 and 1.33 Mev) or use of adjustable intensity sources.

2.3 INFRASONIC GAUGE

The Resonant Infrasonic Gauging System (RIGS) concept is based on the principle that the ullage gas in a propellant tank behaves as a spring and will, in combination with a weighted diaphragm, form a spring-mass system which will resonate at a characteristic frequency. The frequency at which resonance occurs is directly related to the volume of ullage gas in the propellant tank, and thus provides the data required to gauge the remaining propellant quantity. The frequency is detected by a closed-loop, phase-lock technique.

The RIGS covers the range of tank sizes and configurations where the Nuclear Gauge appears to be less attractive. For instance, the RIGS appears to be well suited to gauge LOX in large tanks where the Nuclear Gauge is less desirable. On the other hand, the RIGS is not well suited for gauging LH₂ while the Nuclear Gauge is at its best. The reason that the RIGS can not be used to gauge LH₂ is due to high compressibility of the LH₂, large variation of LH₂ density with temperature and variation in hydrogen ullage gas parameters at cryogenic temperatures. These factors affect the RIGS performance and reduce its accuracy to a point where it appears to be marginal in LH₂ applications.

2.4 RECOMMENDATIONS

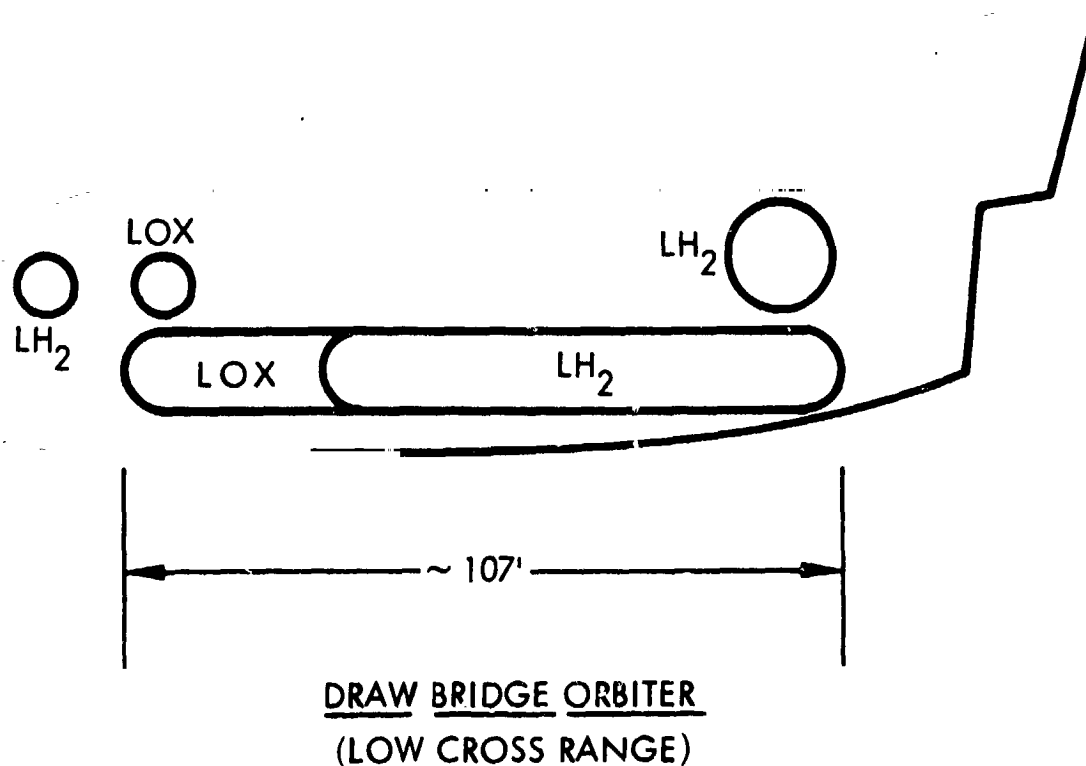
As a result of the study several new propellant gauging concepts have been identified. These concepts require additional development and/or testing before their applicability to the Shuttle can be firmly established. The recommendations given below outline a program for continuation of work started under the above mentioned contract:

- Develop the Resonant Infrasonic Gauging System (RIGS) for gauging of Shuttle LOX tanks. The RIGS, when operated in the isothermal mode, appears capable of gauging LOX, in zero-g, in tanks that employ extensive surface tension screens and other devices.
- Develop the Ultrasonic Liquid Level Gauge for use during engine burn where RIGS can not operate or in conjunction with propellant destratification methods.
- Develop propellant destratification techniques, such as the sprinkler system since it improves the accuracy and/or simplifies virtually any gauging system that may be selected.
- Develop the Nuclear Gauging device for LH₂ tanks. This will be accomplished under Air Force/NASA Houston sponsorship.

3.0 TECHNICAL DISCUSSION

3.1 SPACE SHUTTLE VEHICLE TANK CONFIGURATIONS

Of primary concern in any gauging concept is the particular tank geometries under consideration. Since the Shuttle Vehicle was undergoing basic design during the time this program was performed, close liason was maintained with McDonnell Douglas and North American Rockwell Corporation personnel involved in Phase B Space Shuttle Studies to keep abreast of the latest tank configurations. Some of the tank designs that were studied during the course of this program are shown in Figures 1 through 6. Figure 1 shows the "Draw Bridge Orbiter" vehicle layout. The individual tank details are given in Figures 2 and 3. North American Rockwell's LH_2 tank concept is given in Figure 4.

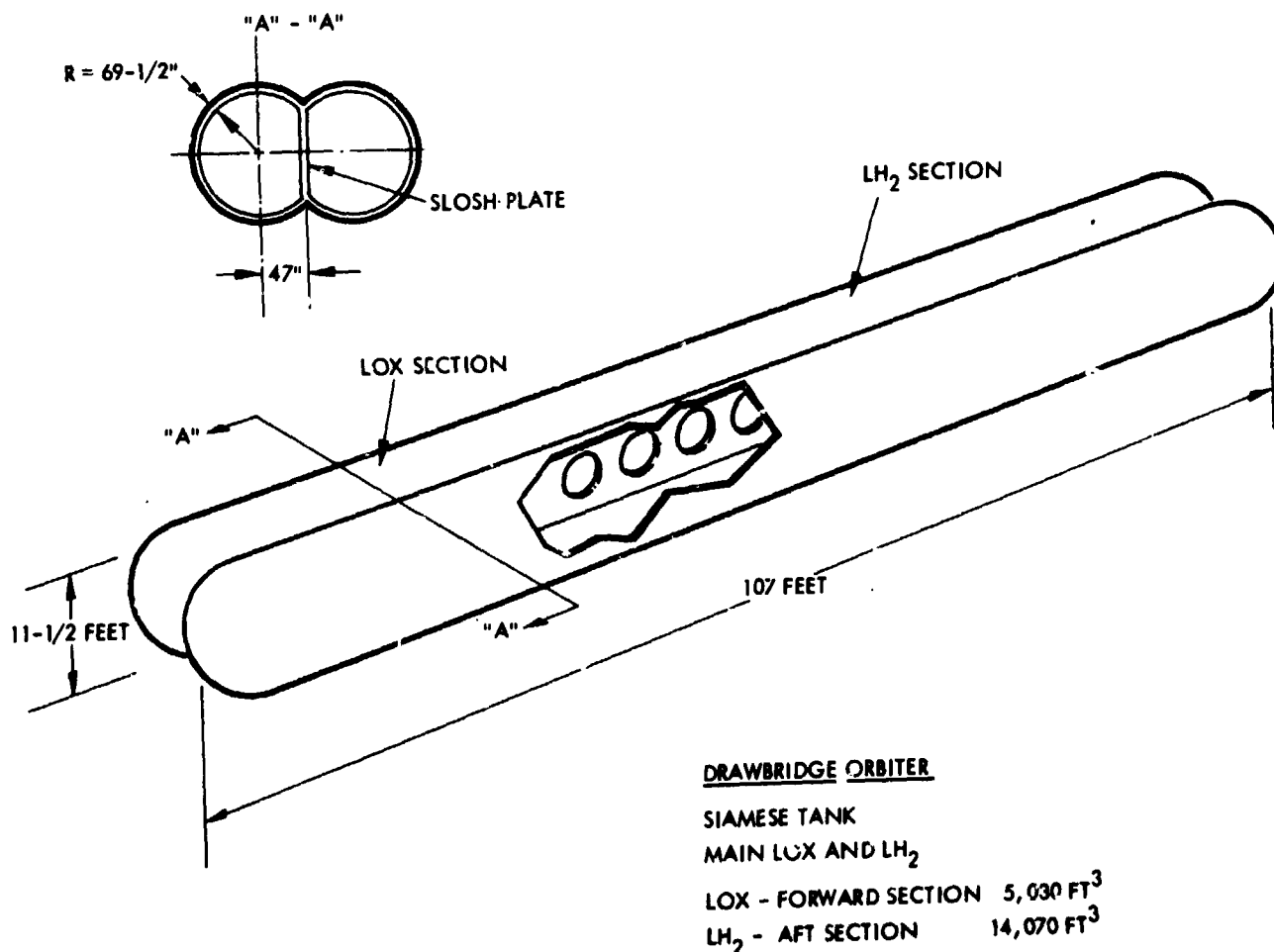


MAIN LH_2 TANK	14,070 CU. FT.
MAIN LOX TANK	5,030 CU. FT.
SECONDARY LH_2	1,770 CU. FT.
SECONDARY LOX	525 CU. FT.
GO AROUND LH_2	525 CU. FT.

Figure 1. Draw Bridge Orbiter Tank Layout

Conceptual plans call for helium ullage in LOX systems and LH₂ vapor ullage in LH₂ systems. The MDC tanks will have PHI (insulation) composed of 70 layers of gold-kapton. Each layer will be 0.003 inch thick. It will have an impregnated resin sheet with 1-inch slats on one-inch centers.

As illustrated in Figure 4, NAR designs incorporated very complex surface tension screen, and other structure arrangement in the interior of the tank which makes gauging of propellant by any means extremely difficult.



Figure

Figure 2. Draw Bridge Orbiter Main Tank

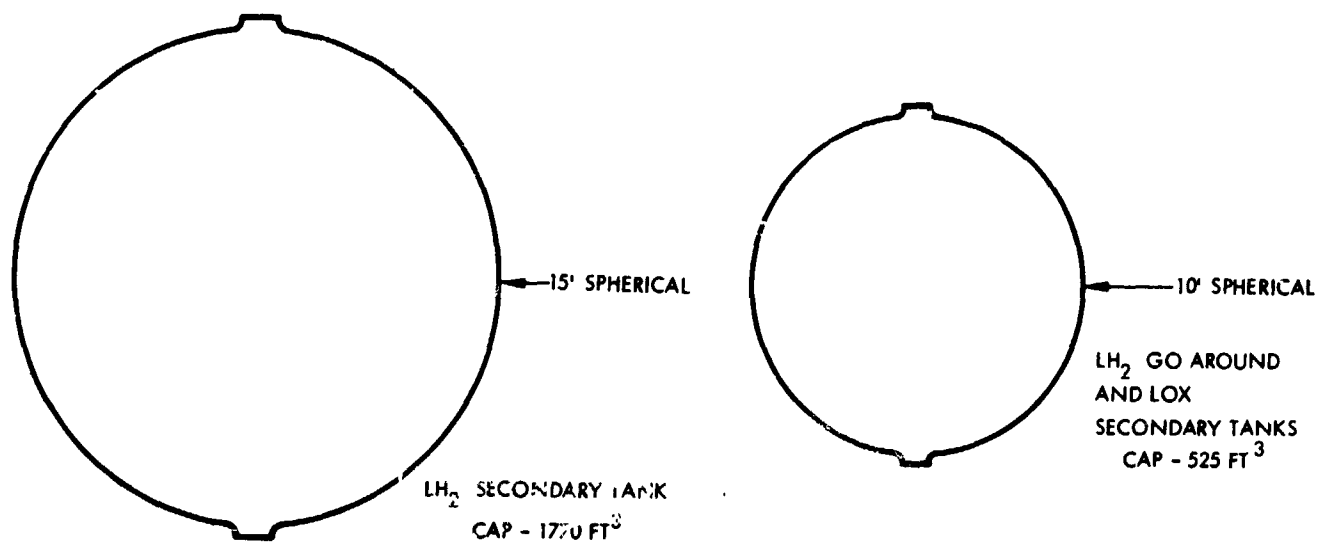


Figure 3. Draw Bridge Orbiter Auxiliary Propulsion System Tanks

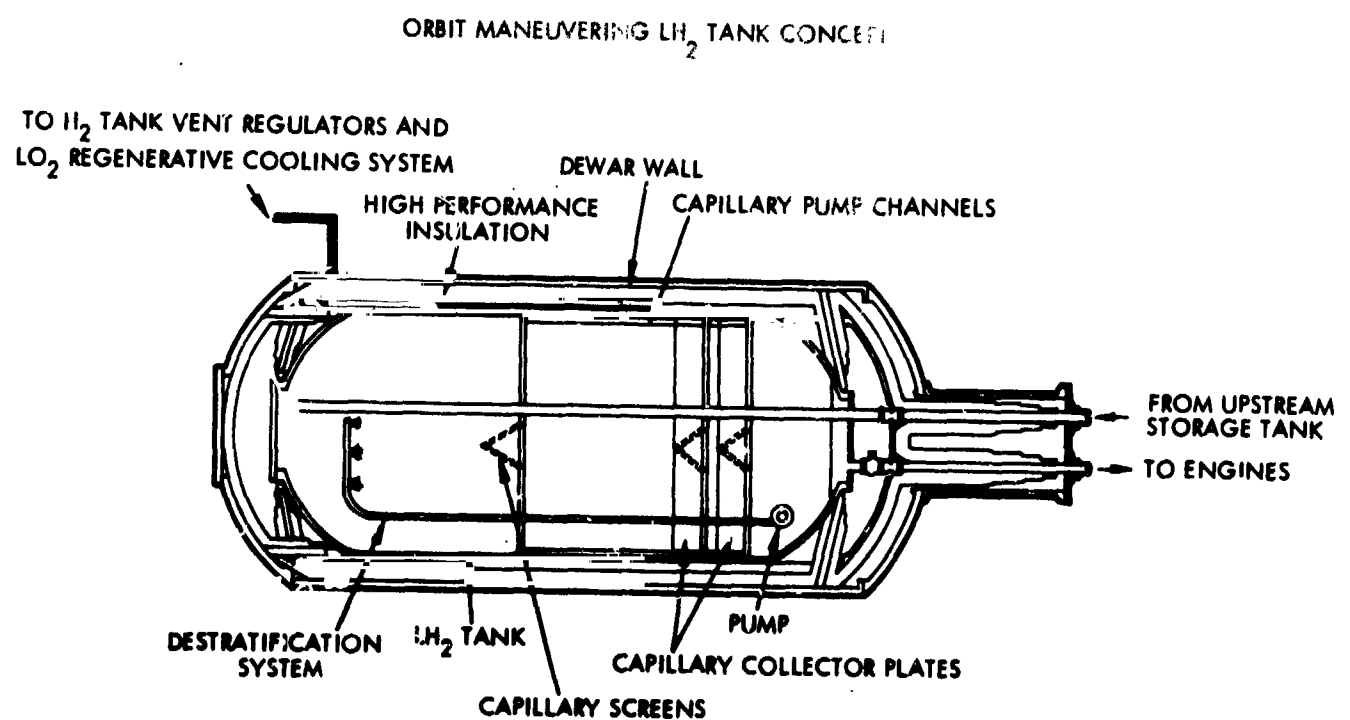


Figure 4. NAR LH₂ Tank Concept

Conversations with Space Shuttle Project personnel indicated that gauging of the booster vehicle tanks is not (at least during zero-g conditions) required. Therefore, the booster vehicle tanks were not considered during the course of this program.

Later in the program updated tank configurations were received from NAR and MDC. The external tank configurations are shown in Figures 5 and 6.

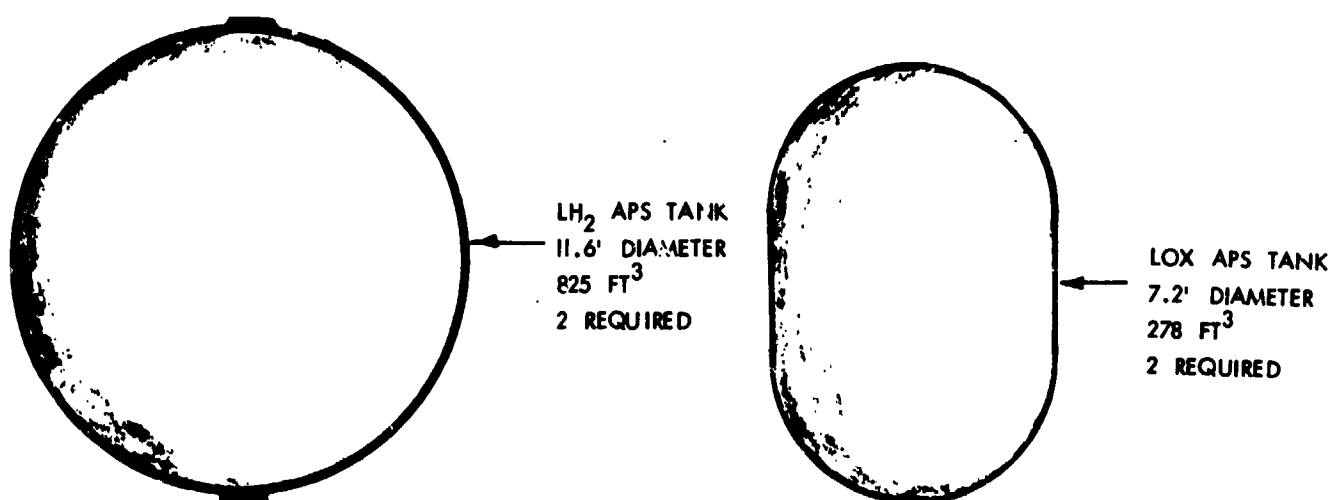


Figure 5. NAR APS Tanks

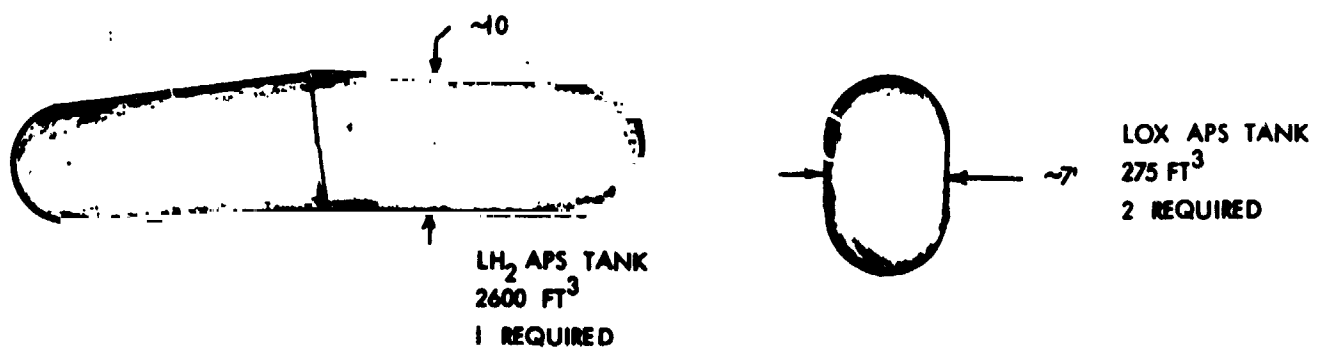


Figure 6. MDC APS Tanks

3.2 GAUGING REQUIREMENTS

The objective of this program was to study gauging system designs characterized by simplicity of fabrication, installation, and maintenance. Operational considerations were weighted to insure that candidate systems could serve adequately through the mission life cycle and that they would survive long periods of storage during non-operational use. In addition to the above stated objectives, this study was directed towards establishment of gauging systems that require no special tank design features and present no safety hazards. The system accuracy should not be degraded by variations in propellant or tank temperatures. If such degradation occurs, temperature compensation for the final readout or computation must be available.

In the analysis, methods of fuel destratification were also considered. Preliminary analysis of acoustic pumping schemes indicated that this technique offers a means of preferentially positioning the fluid when the fuel remains under zero-g conditions for a prolonged period of time. Consideration of the time required to settle the propellant and the mechanics of the process (i.e., conservation of momentum of liquid particles at the liquid-gas interface) suggested alternate techniques such as infrared pumping and fluid pumping. One approach, a concept of "sprinkler" destratification, was evaluated and is described in detail in Section 3.4.2.

To be applicable to gauge fuel for the Space Shuttle Vehicle, the gauging system must meet the following constraints and/or operate under the following conditions:

1. The cryogenic propellants will have temperature gradients ranging from the triple point of the boiling point and the ullage may have temperature gradients of approximately 20° Kelvin.
2. The pressure of the tanks will be controlled by venting. This pressure will be known and will be approximately 2 atmospheres.
3. The ullage will be a mixture of propellant vapor and helium gas.
4. The engines can use only liquid propellant, therefore, the gauging requirement is for a measure of useable liquid propellant remaining.
5. The desired propellant gauging accuracy is 2% with respect to total volume.

6. A single mission duration will be approximately seven days.
7. The vehicle life will be at least one hundred missions.
8. The propellant quantity measurement must be valid in conditions ranging from zero- to 1-g.

Discussions with Shuttle contractors and NASA project personnel indicate that the study of propellant gauging requirements be confined to auxiliary propellant tanks of the orbiting vehicle.

The physical properties of oxygen and hydrogen and other fuel system design parameters are summarized in Tables A-1 and A-2 of Appendix A.

3.3 ANALYSIS OF GAUGING SYSTEMS

From the conditions outlined in Section 3.2, it can be seen that the design of a gauge to operate on the Shuttle Vehicle and meet all the constraints is not an easy task. In fact few of the existing gauging systems appear to be applicable. For instance, the PVT system will not work because the tanks are vented. Level measuring techniques will not work because the propellant is stratified under zero-g unless propellant settling can be employed.

As a result the efforts of this program were concentrated on designing an entirely new gauging system concept and/or adapting one or more of the existing concepts to operate under the constraints imposed by the Space Shuttle Vehicle. As part of this task several "brainstorming" sessions were organized in an attempt to come up with a useful approach. Appendix B gives a listing of the participants of the sessions.

The following sections describe various gauging system concepts and how they apply to gauging of Space Shuttle Vehicle tanks.

3.3.1 Gauging Systems Based on Gamma-Ray Attenuation

Propellant gauging using a gamma-ray attenuation technique offers many advantages that are not available by other means. Some of these advantages are:

- The propellant quantity measurement is performed completely external to the tank.
- No moving parts
- Propellant mass is measured directly.

- Propellant quantity measurement is independent of propellant orientation or obstructions such as baffles, zero-g screens, etc.
- Propellant quantity measurement is independent of propellant temperature and pressure.

Propellant gauging using nuclear attenuation works in the following way: An array of gamma-emitting radioisotope sources are positioned on one side of the tank and radiation detectors on the other. The gamma radiation emitted from the sources penetrates the tank walls, is partially attenuated by the propellant and then is detected by the detectors. The amount of gamma radiation that is received by the detectors is related to the quantity of propellant inside the tank.

There are two basically different methods for mechanizing this propellant gauging concept. One is based on using the natural (exponential) gamma ray absorption characteristic of the propellant. The second is based on obtaining a linear gamma ray absorption relationship. The latter is accomplished by judiciously employing a window discriminator in the detection circuit to accept photons that fall within a narrow energy range thus making the gamma ray absorption a linear function of absorber thickness. Both systems use radiation sources on one side of the tank and detectors on the other side; however, their complexity and operation principles are entirely different.

The system using exponential gamma ray absorption operates on the principle of subdividing the tank into small columns, measuring the propellant quantity in each column with a separate radioisotope-detector pair, and then summing the contribution of all columns by electronic means to provide a measure of the total mass of propellant.

The system using linear gamma ray absorption is designed so that the summing of the contributions of each detector is inherent in the system and the sum of the detected radiation by the detectors is proportional to the total propellant mass in the tank.

The significant difference between the two systems is that in the first case the radioisotope sources have to be collimated so that they illuminate only one detector at a time. Also, each radiation detector is required to have its own set of signal conditioning and processing electronics. The second system (linear absorption), at least in principle, can operate all

detectors in parallel and the radioisotope sources do not need to be collimated. This was the principle of operation of the Conrac Corporation (formerly Giannini Controls Corp.) Nucleonic Zero-G Propellant Gauge for Apollo RCS tanks.

The system, based on linear gamma ray absorption, is considerably easier to build (from a hardware point of view) than the exponential approach. However, it is severely limited by the tank size. The linear absorption system can be used to gauge LH_2 in large diameter tanks (>15 feet), but there is no practical way of using it for gauging LOX in tanks larger than ~1 foot in diameter. The system using exponential gamma absorption is not severely limited by the tank size and in principle can be used to gauge both the LOX and LH_2 .

During the course of this program TRW was under Contract to Edwards Air Force Base, Rocket Propulsion Laboratory (Contract No. F04611-71-C-0010) to develop a Nuclear Propellant gauge. This gauge is for measuring LH_2 and LF_2 in 8-foot diameter spherical tanks and is based on the exponential absorption technique.

Close liason was maintained with personnel involved in the development of the AF gauge. The purpose was to see how well this gauge design could be adapted for the Shuttle Vehicle tanks. The following conclusions have been reached about the applicability of the nuclear gauge to the Shuttle Vehicle:

- The nuclear gauge can be utilized to gauge LH_2 and possibly the LOX APS tanks of the Shuttle Orbiter Vehicle.
- Gauging of LOX tanks will probably require positioning the radioisotope sources inside the tank and the detector on the outside, as illustrated in Figure 7.
- LH_2 can be gauged with both the sources and detectors located on the outside of the tank.
- Nuclear gauging appears to be the only method of gauging LH_2 in tanks that contain extensive baffles and surface tension screen structure (such as shown in Figure 4).
- On the order of 17 source detector pairs will be required to obtain a 2% gauging accuracy. *Also see Appendix C*
- Cesium-137 radioisotope (of 0.1 to 1.0 Ci source strength) appears as the optimum compromise to be used as sources for gauging LH_2 in Shuttle-size tanks.

- The sources will be collimated and shielded so that radiation dose rates around the tanks will not impose radiation hazards nor severe restrictions for personnel that may be working in the immediate vicinity of the tanks.
- Gauging of LOX by nuclear means is considerably less attractive than gauging LH₂ because the relatively high density of LOX requires the use of higher energy (Cobalt-60) and higher strength sources. Also unless the LOX tanks are less than ~5 feet in diameter the radiation sources will have to be located inside the tank.
- Unless some of the more sophisticated nuclear gauging methods (such as use of variable intensity sources) are proven to be significantly superior to the present design, it is recommended that other means of gauging LOX in the Shuttle Vehicle tanks be investigated.

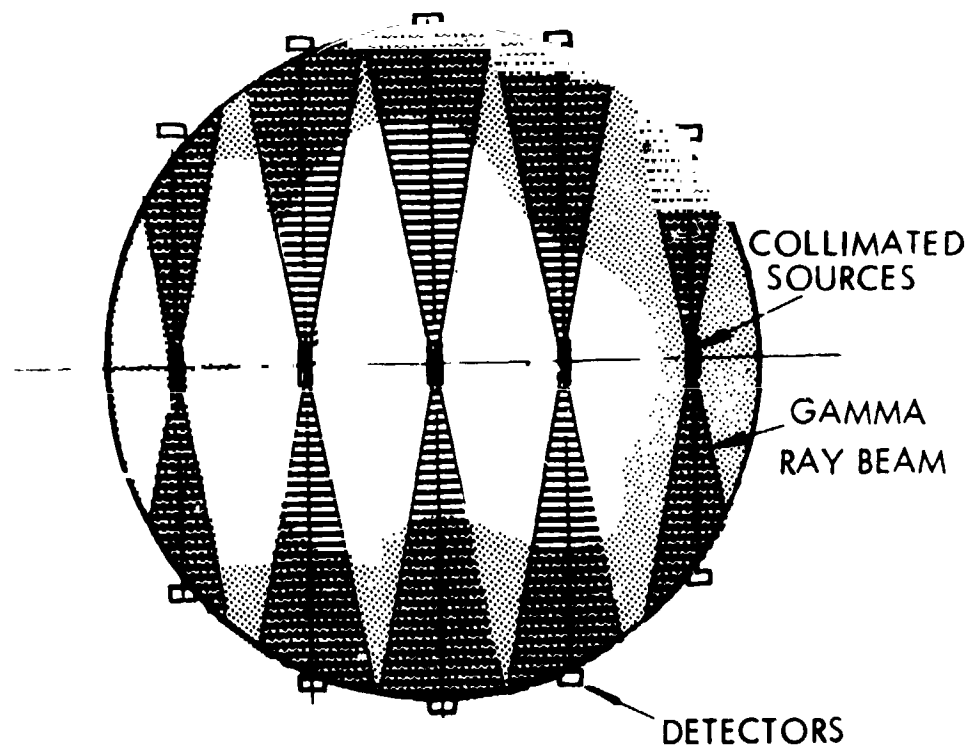


Figure 7. Nuclear Gauge with Sources Inside the Tank

3.3.2 RIGS

The Resonant Infrasonic Gauging System (RIGS) concept was originally developed by TRW under NASA Contract NAS 9-6750. This system was designed to measure storable propellants under zero-g conditions for the Apollo Service Module application. The RIGS was thoroughly analyzed, designed and a breadboard model was built. The tests conducted with the breadboard model showed every indication that the system will meet all of its design requirements.

The basic geometry of the RIGS system is illustrated in Figure 8. The device consists of a constant amplitude/variable frequency driver, an isolated driver cavity, and a weighted flexible diaphragm. The weighted diaphragm is designed to resonate as a function of ullage compressibility compared to the known drive compressibility. As the ullage compressibility changes as a function of total ullage volume the resonating frequency changes also and the comparison of the ratio of this resonance to the fixed drive volume is translated into a measure of ullage volume. The resonant frequency is essentially a function of ullage volume, ullage pressure and the specific heat ratio of the ullage gas. The resonant frequency is determined indirectly by determining the anti-resonant system frequency, which is measured from minimum amplitude or 90-degree phase shift correlation of the dynamic gas pressure in the small cavity attached to, but isolated from the main propellant tank, and the main tank ullage. The detailed analysis of the RIGS system for storable propellants is available in the Contract Reports (NAS 9-6750, September 1967).

Three key problem areas of adapting RIGS to cryogenic propellants have been identified.

1. Compatability and fatigue properties of RIGS bellows at cryogenic temperatures.
2. Variation of ullage gas properties (ratio of specific heats).
3. Presence of baffles and surface tension screens in the tanks

The discussion below shows that these problem areas appear to have relatively easy engineering solutions.

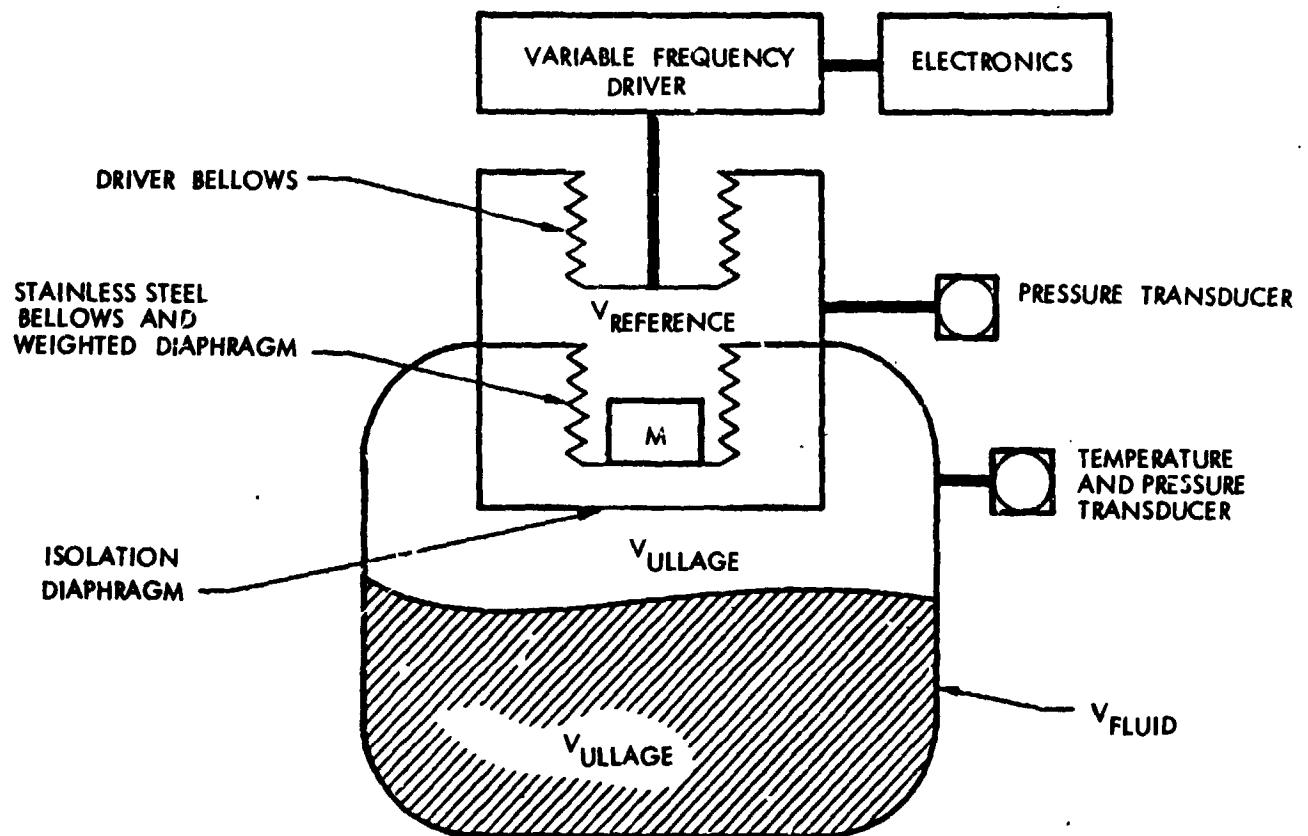


Figure 8. RIGS Block Diagram

3.3.2.1 RIGS Bellows

The bellows problem may be readily solved with a little development work. For instance several elastomers tested during the course of this program appeared to retain most of their elastic properties when immersed in LN_2 and according to the manufacturer, were compatible with LOX. It would be a relatively simple matter to obtain several elastomer samples, immerse them in LOX and flex them to see how much their elastic properties change and if they can withstand the environment.

If the elastomers fail, there is another, more direct approach, i.e., metal bellows. Assuming that the Shuttle Vehicle will fly 100 missions at 7 days per mission, and that the RIGS will be continuously in operation during the mission and will operate at an average frequency of 1 Hz, the bellows will be flexed approximately 6×10^7 times during the life time of the system.

Figure 9* shows the allowable stress limit on 301 stainless steel sheet as a function of number of cycles of flexure for various temperatures. Although this particular set of data does not include 6×10^7 cycles, extrapolation of the data at -320°F clearly indicates that by keeping the stress limit below $80,000 \text{ lbs/in}^2$ the fatigue life of the bellows will not be exceeded. Thus 301 stainless steel bellows appear to be adequate for use with RIGS as long as the bellows are made thin enough such that the working stress does not exceed the limit mentioned above.

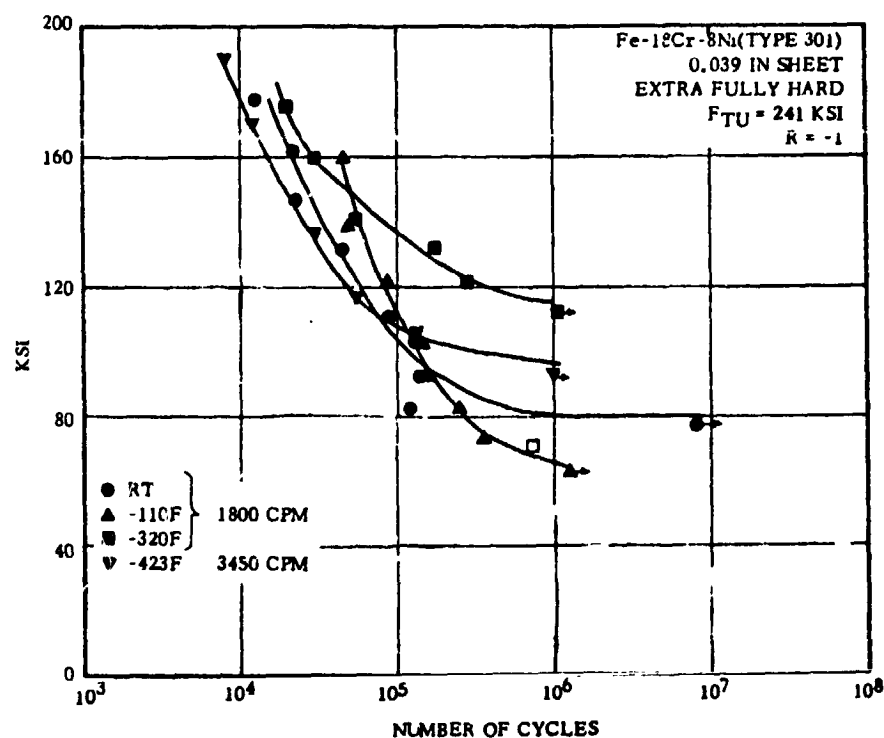


Figure 9. Fatigue Properties of 301 Stainless as a Function of Temperature

*Reproduced from "Aerospace Structural Metals Handbook," Volume I, March, 1967.

It is interesting to note* that the commonly known embrittlement at cryogenic temperatures occurs only in few materials. Among them is carbon steel which is widely used as structural material and has caused several disastrous failures of cryogenic vessels. Actually most other ordinary structural materials such as aluminum, copper, nickel, most of their alloys as well as "series 300" austenitic stainless steels do not exhibit the embrittlement phenomena at cryogenic temperatures. In fact some materials (301 stainless shown in Figure 9) exhibit improved fatigue resistance with decrease in temperature.

In conclusion it appears that the design of bellows for RIGS is a relatively straight-forward engineering task which can be readily implemented.

3.3.2.2 RIGS Error Due to Ullage Gas γ

The resonating frequencies of RIGS are proportional to the ullage volume and the average γ (ratio of specific heats) of the ullage gas. As the γ varies (with ullage gas temperature and/or composition due to addition of pressurant gas) the RIGS resonating frequency will change and can cause an error in propellant quantity measured.

The original RIGS analysis and computations of the error as a function of the variation of specific heats of the ullage gas (γ) were based on assuming that the system obeys adiabatic gas laws. For the intended storable propellant use of RIGS (Apollo Service Module Tanks) at the time the analysis was performed, this was a good assumption. However, if isothermal gas laws were valid under certain operating conditions, the ratio of the specific heats would approach unity and γ would not enter into the relationship. Thus there would be no error introduced due to variation of ullage gas parameters. In reality, the RIGS operates somewhere between the idealized adiabatic and isothermal conditions. If the RIGS resonating frequency is selected high compared to the heat transfer rate (presumed to be between the ullage gas and the propellant) the gas behavior will obey the adiabatic law. On the other hand, low frequency will approach an isothermal condition because the propellant will act as a heat sink and the ullage gas will tend to remain at a constant temperature, thus the effective γ will approach unity.

*See Russel B. Scott, "Cryogenic Engineering" Chapter 10, D. Van Nostrand Co. Inc.

The "real life" RIGS behavior may be explained by referring to Figure 10. The ullage gas consists of LOX vapor (O_2) and Helium pressurant gas. The average γ will be mostly affected by the composition of ullage gas. For oxygen (O_2) γ is ~ 1.4 ; for Helium the γ is ~ 1.67 . Thus at adiabatic conditions the γ will be somewhere between 1.4 and 1.67 depending on the O_2 gas to the pressurant ratio. When isothermal process conditions are approach $\gamma \rightarrow 1$ regardless of what the ullage gas ratio is. Thus as long as the RIGS operating frequency range is selected such that γ is close to unity, there will be no appreciable error in propellant quantity measurement.

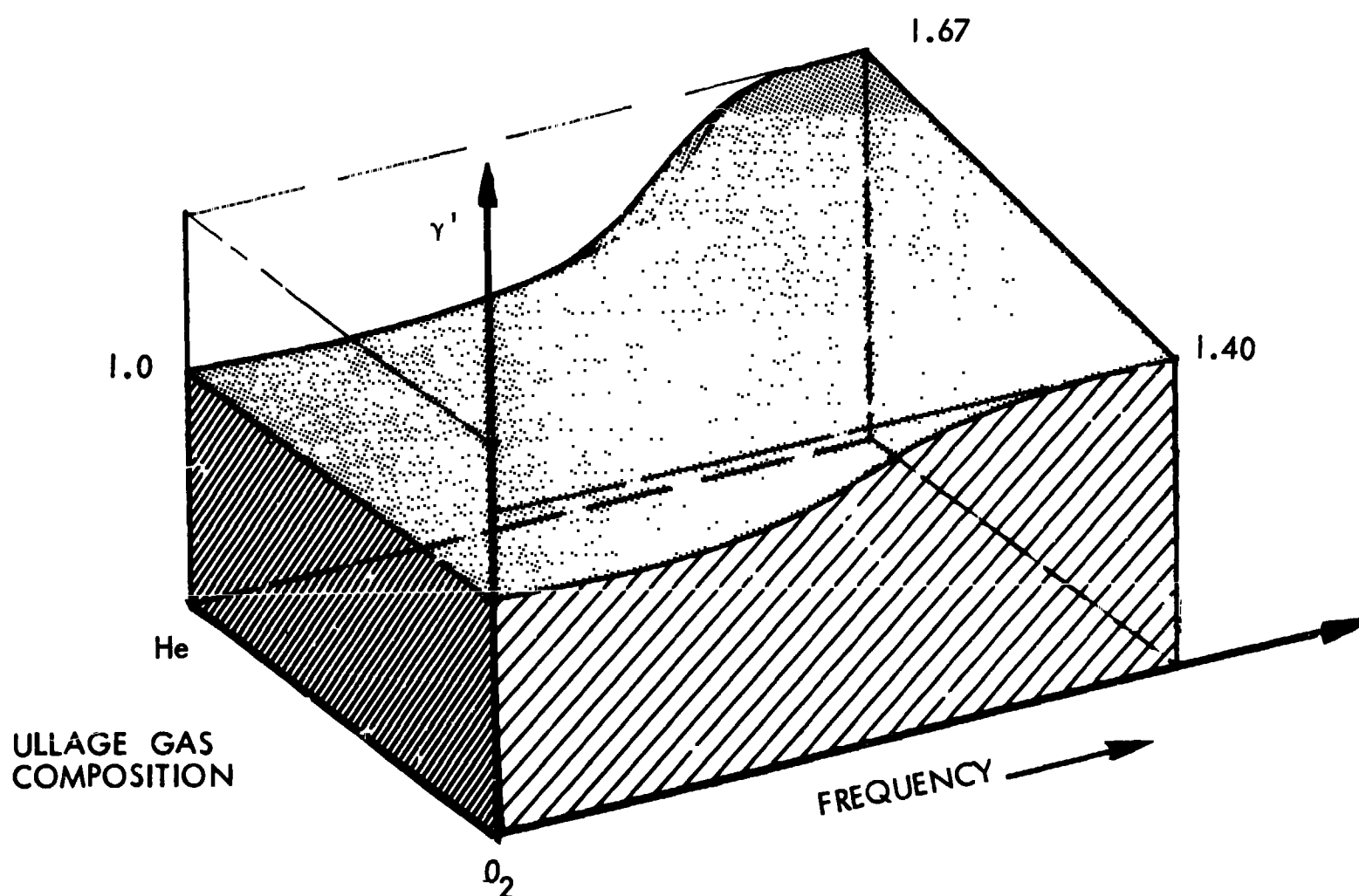


Figure 10. γ as a Function of RIGS Resonating Frequency and Ullage Gas Composition.

In view of the difficulty of performing the heat transfer computations required to derive an accurate plot such as shown in Figure 10, a simple test could easily provide all the necessary data to predict the RIGS error as a function of γ of the ullage gas. The test would consist of a RIGS sensor attached to a tank which would be filled with a fluid (starting out with water and then LOX). To vary the gamma, various gasses and/or gas mixtures could be used to pressurize the system. It would be only necessary to measure the percent change in the RIGS resonating frequency as a function of the ullage gas mix and the operating frequency.

Pending successful outcome of this experiment, the RIGS design would progress to a full scale prototype for full scale tests and eventual use on the Shuttle Vehicle for LOX tank gauging.

3.3.2.3 Effect of Surface Tension Devices in the Tank

Presence of surface tension devices in the interior of the tank complicate the design of most gauging systems. However, they are not expected to affect the performance of RIGS appreciably. One can argue in the following way:

RIGS is unique because by placing a mass on the resonating diaphragm it can be made to resonate at very low frequencies (on the order of fractions of a Hz). The use of this very low frequency allows the pressure wave to be transmitted through fluid or even a gas/liquid/gas interface without appreciable attenuation (as demonstrated by tests performed under Contract NAS 9-6750, "Feasibility Study of Positive Gauging System, Phase II"). Thus one may conclude that the pressure wave could be transmitted through a surface tension screen also without appreciable attenuation, if the RIGS frequency is made sufficiently low.

If the screen is dry, the pressure wave will go right through it and will not affect the RIGS operation. If the screen is saturated with liquid, the screen will appear as another gas/liquid/gas interface and should allow the pressure wave to go through it also; as it did during RIGS feasibility demonstration tests.

In summary it appears that by using low resonating frequencies the effect of changes in γ on the RIGS accuracy will be minimized and also will allow gauging of tanks with surface tension screens. As a result, RIGS appears as a very attractive gauging system concept for gauging LOX in the Shuttle tanks.

It is possible to argue that the same isothermal operation of the RIGS could be adapted for gauging LH₂ tanks also. However, the reservations of using RIGS for gauging LH₂ are due to the following reasons:

- LH₂ exhibits a relatively high compressibility in certain temperature ranges which undoubtedly would affect the RIGS operating frequencies. Although it may be possible to "calibrate out" this effect, test data with real LH₂ tanks is required to be certain that this can be accomplished within the required accuracy.
- LH₂ density varies extensively with temperature (on the order of 2% per °C change in temperature). Since RIGS measures the ullage volume, hence the volume of the LH₂, a very accurate LH₂ temperature measure would be required to convert the volume measurement to mass. It is doubtful that such a temperature measurement is possible to perform when the liquid is stratified under zero-g conditions and has large temperature gradients.

As a result it appears that overall the RIGS is a poor candidate for gauging LH₂. Meanwhile LOX is virtually incompressible and the density varies by only approximately 0.4% per 1°C change in temperature. Thus it is considerably easier to convert accurately from LOX volume measurement to mass.

3.3.3 Ultrasonic Systems

The principles involved in ultrasonic transmission offer a possible new means of measuring propellant quantity with the same advantages offered by nuclear gauging.

The fundamentals involved are:

$$V = \sqrt{\frac{E}{\rho}}$$

where V is velocity of a compressional wave in an elastic medium. E is the bulk modulus of the material and is given by

$$E = \frac{(P_2 - P_1) V_1}{V_1 - V_2}$$

where ρ is the density of the medium and is a function of temperature.

The attenuation of a sonic wave follows an exponential relationship

$$e^{-\alpha t}$$

where α is a constant
and t is time

The velocity of an ultrasonic signal can also be correlated to the temperature (T) of the medium through the relationship

$$V = V_0 \sqrt{1 + \frac{T}{273}}$$

A consideration of these two fundamental relationships has suggested a method of determining the temperature and density of the propellant by introducing sharp pulses of ultrasound into the tank and then monitoring the amount of attenuation and the time of arrival of signal at a given receiver. An analogy would be the customary practice of tapping a melon at the marketplace.

The technique under consideration would employ a series of piezo-electric crystals around the peripheral wall of the tank. The crystals would be in intimate contact with the tank wall by means of a transmission rod. By driving the crystal with a very short ($<1 \mu$ sec) excitation pulse, the crystal will produce oscillations of its natural frequency, which in turn induce mechanical waves into the surrounding medium. In this case, the medium of interest would be the tank wall and the propellant. The mechanical wave is then transmitted along the tank wall and, at the same time into the adjacent media which is ullage or liquid. By "listening" with a companion crystal at a known dimension from the excitation crystal, two parameters can be monitored in the metal wall. The time of arrival of the pulse at the companion crystal will determine the average temperature of the metal, and the amplitude of the pulse will monitor the density of the medium in intimate contact with the area immediately adjacent to the sonic wave generator. The mechanical wave will be coupled into the liquid and will travel through the liquid to the companion crystal at a much later time (i.e., the velocity in LOX will be about 1/5 that of aluminum, and the velocity in O_2 will be about 1/2 of that in LOX). Since the time of arrival

through fluid is much later than through an equal distance of metal, the received signal can be gated on only during the time of interest, thus eliminating all extraneous reflections in the system. Since the signal frequency is known, and very high (>200 Hz), system noise can be easily filtered. It also appears feasible to monitor the reflection of the fluid signal to determine depth, much as in conventional depth finders. Very preliminary lab tests have determined the feasibility of monitoring temperature and liquid level in gravity conditions. The ability to measure propellant quantity in zero-g will obviously be more complex.

With reference to Figure 11, the following relationships can be established.

C_m = Velocity through metal; C_f = Velocity through fluid; α = attenuation through fluid and metal.

T_1 is pulsed electrically.

t_1 is a function of C_m , and $t_1 \ll$ than t_2 .

Measurement of these two parameters (time of arrival and attenuation) can establish average wall temperature and whether or not fluid is in contact with the wall and along the distance over which the liquid is in contact.

$t_2 \gg t_1$ and is a function of fluid temperature.

$t_3 > t_2$ and is a function of fluid distance when corrected for temperature effect on C_f .

t_5 is a function of C_m and α between T_1 and T_4 .

By programming the excitation pulse to energize T_1 , T_2 , T_3 , and T_4 , and then having each crystal act as a receiver and be gated on only during the pre-selected time of interest, a logic network can be derived which would describe the approximate position of the fuel and its temperature. The number of detectors needed would be determined by a given tank geometry. By operating on the "leading edge" of the transmitted pulse (i.e., selection of the third oscillatory peak illustrated in Figure 11) simple threshold detector electronics can be employed which establish the time relationship with respect to the transmitted pulse. By correlating the threshold detection time to amplitude above a given threshold, the attenuation factor can be determined.

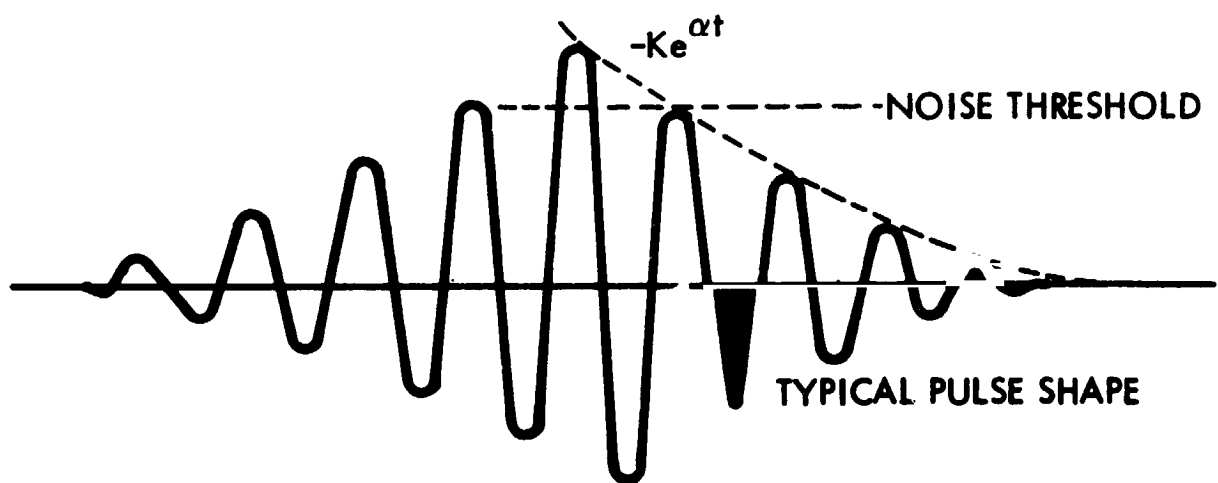
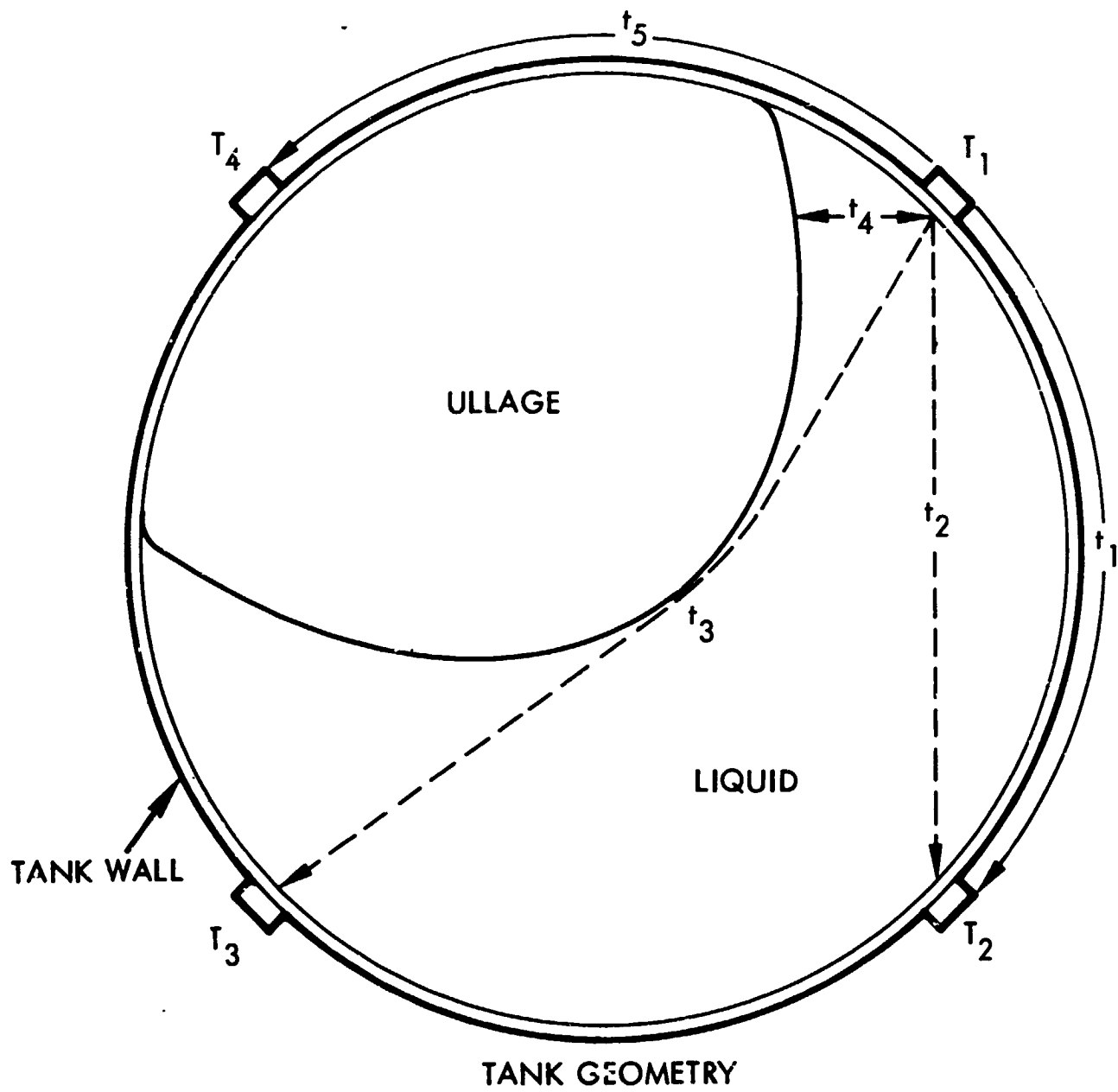


Figure 11. Ultrasonic Fuel Gauging Concept

The above technique can be considered if it is assumed that the capillary forces will tend to hold the remaining fluid against the tank wall and that the fluid will not tend to "float" in several random masses.

Another possible method has emerged from the study of ultrasonics. This scheme would be comparatively simple and would be a measure of total attenuation of mass. With reference to Figure 11, a series of ultrasonic transmitter/receivers are placed around the wall of the tank. By driving the transmitter crystal for a short period of time at some optimum frequency and then listening with the receiver crystals, the total energy received by the crystals will be representative of the tank mechanical "Q". A simple analogy here would be a bell ringing. As the "bell" surfaces are modified by damping, the total energy being received will change, and will be a function of the various resonances and attenuation factors introduced into the system by the damper. In this application, the time window of the received energy must be programmed such that the energy traveling along the metal wall will be damped sufficiently below the selected receiver threshold to be eliminated from the "Q" attributable to the liquid. By measuring the total energy received above a given threshold, it is postulated that this will be a measure of the system "Q" attributable to the liquid mass. Since the liquid-vapor interface serves as a reflective surface, the bulk of the fluid coupled energy will be reflected back into the liquid and thus into the peripheral receiver crystals. The total contribution of energy would be somewhat similar to the RF mode counting schemes except that the energy would be mechanically coupled to the tank wall and thus provide a simpler method of detection.

This technique will be sensitive to temperature variations, as are all density measurement schemes. By properly programming the sequence of counting, it would be relatively simple to measure and correct for the temperature of both the tank wall and fluid.

Both ultrasonic schemes are in the very early stages of development. It should be noted, however, that sufficient laboratory work has been done to indicate that the required measurements are possible. In summary the ultrasonic techniques offers the following distinct advantages:

- No penetration of the tank wall, thus structural integrity would not be compromised.
- The requirement for electrical conditioning is all external to the fuel and tank wall.
- Transducers would be replaceable during system operation.
- A measure of temperature and density could be obtained simultaneously.

This ultrasonic gauging technique would require extensive testing and development work before its feasibility can be firmly established. For this reason it has been abandoned in favor of systems that appear to be easier to develop.

3.3.4 Ultrasonic Probe

Recent developments at National Reactor Testing Station have demonstrated the ability of an ultrasonic technique to detect liquid quantity, independent of location.* This device was designed to measure a steam/water ratio in the experiments being conducted to determine the consequence of a reactor loss of coolant accident.

Since average temperature is a stringent requirement in any of the fuel quantity systems, further consideration of the ultrasonic technique has been undertaken. The ultrasonic system has the capability of measuring both temperature and mass with a single transducer. The technique is illustrated in Figure 12. By pulsing the transmitter coil and measuring the time of arrival and amplitude of the signal at the receiver coil, both temperature and density can be obtained. The transit time of the pulse is a measure of the tube temperature, and the amplitude of the pulse is a measure of the density of the material in contact with the tube. By placing a series of receiver coils along a given tube, as shown in Figure 13, a scanning system can be constructed which will determine the two parameters.

The characteristics of an ultrasonic shear wave in cryogenic environments have been investigated. The speed of sound in an elastic medium is:

$$C_l = \sqrt{(\lambda + 2\mu)/\rho} \quad (3-1)$$

$$C_t = \sqrt{\mu/\rho} \quad (3-2)$$

*Arave, A. E., "An Ultrasonic Liquid Level Detector Using Shear Wave Attenuation in a Bar," IN-1442, Instruments, TID-4500, Nov. 1970.

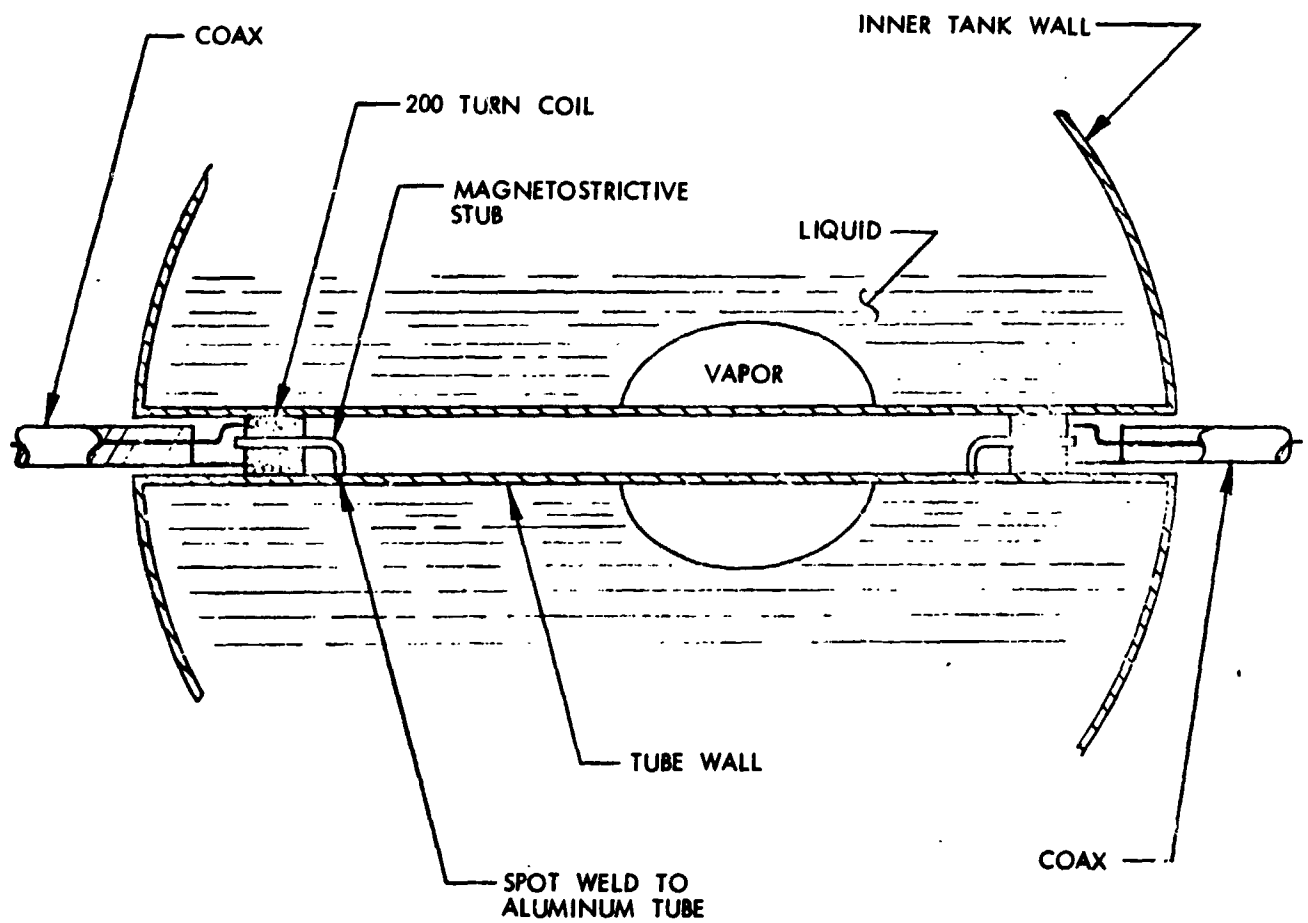


Figure 12. Basic Ultrasonic Liquid Quantity Gauge

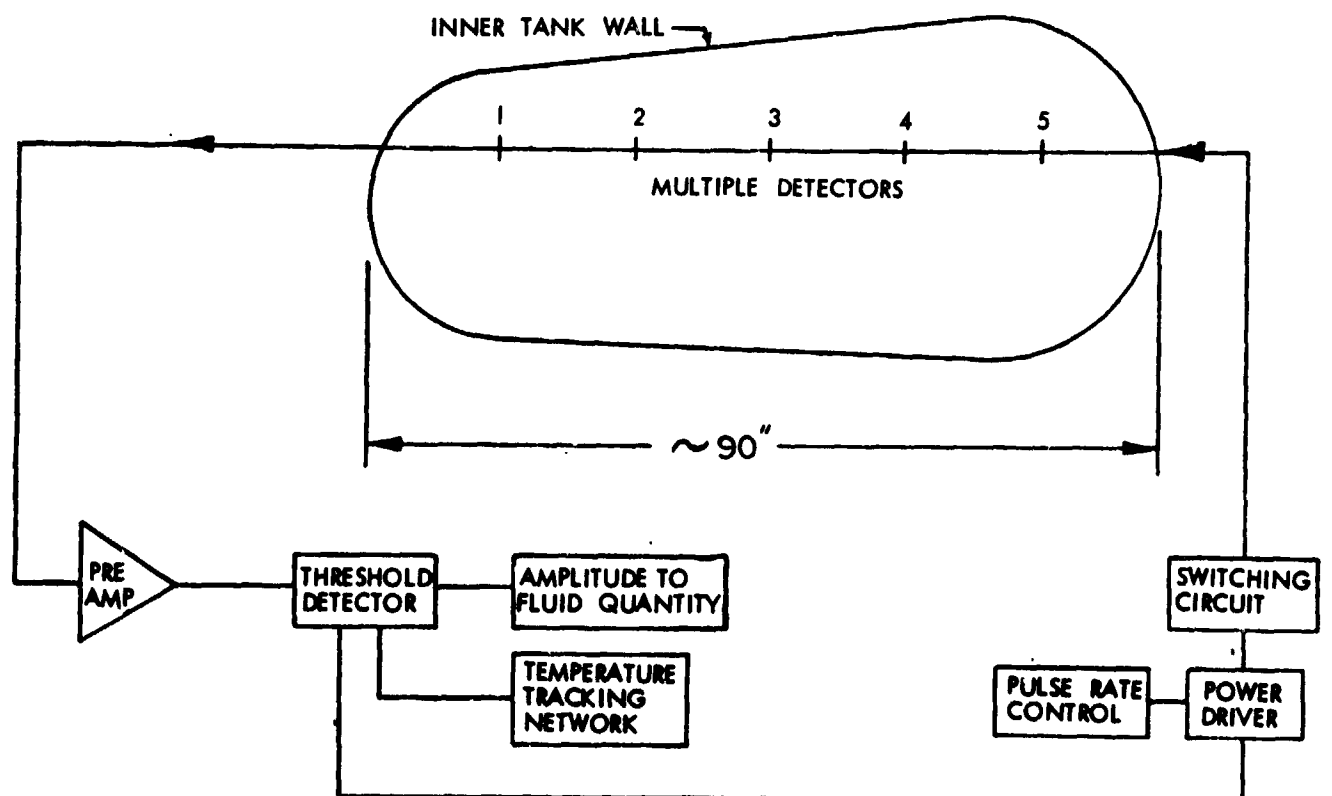


Figure 13. Multiple Detector Ultrasonic Gauge

Where C_l = longitudinal (compressional) speed of sound
 C_t = transverse (shear) speed of sound
 ρ = density
 λ & μ = Lamé constants

The Lamé constants are:

$$\lambda = \frac{Y\nu}{(1+\nu)(1-2\nu)}$$

$$\mu = \frac{Y}{2(1+\nu)} \quad (3-3)$$

Where ν = Poisson's ratio
 Y = Modulus of elasticity

Since density is a function of temperature, the speed of sound can be obtained as a function of temperature by substituting

$$\rho(t) = \rho_0 / (1 + \alpha(t))^3$$

into equations (3-1) and (3-2)

where $\rho(t)$ = density at temperature t
 ρ_0 = density at 0°C (reference)
 $\alpha(t)$ = linear expansion coefficient at temperature t

The handbook values were used to compute the shear wave velocities in typical propellant tank materials (aluminum 2014-T6) and are presented in Figure 14. The shear wave is used as the measured parameter since the geometry under consideration optimizes that mode of transmission. The fundamental relationship is that the compressional wave velocity is approximately twice the shear wave velocity and is displaced in time by a constant. Since the shear wave is the significant measurement, the electronic detection system is designed to see only the time of arrival of the shear wave.

The fundamental characteristics of ultrasonic waves can be utilized to obtain the desired measurement if care is exercised in detecting the correct wave form. Time of arrival and amplitude of the received signal are measurement of the temperature and density of the media through which the signal is passing.

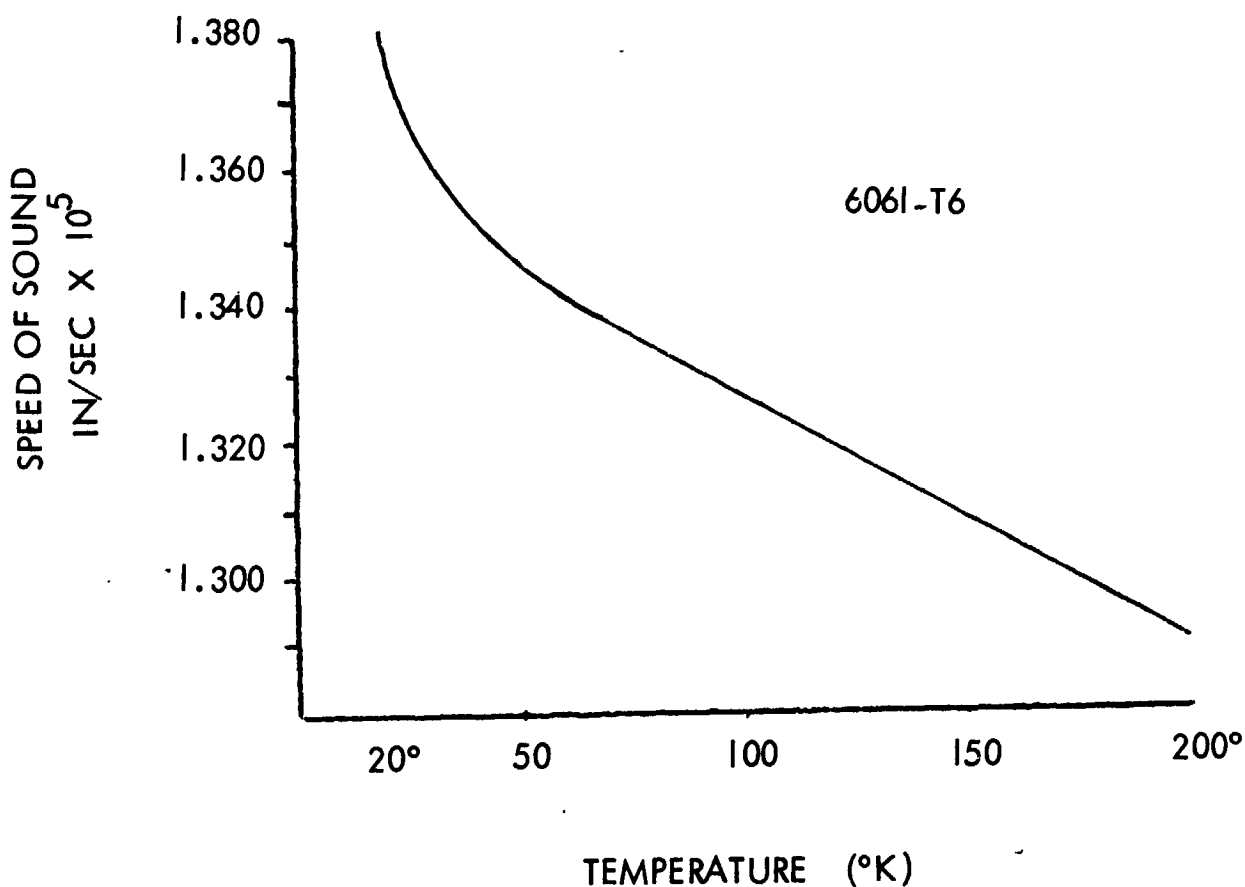


Figure 14. Speed of Shear Wave in Aluminum

A series of laboratory tests on ultrasonic liquid level gauging techniques were performed. Two aluminum sensing bars were constructed and instrumented with the driver and receiver coils. An isometric view of the sensor is shown in Figure 15. The core of the transducer was made of 0.045" diameter Remendur. The coils consisted of 300 turns of #32 copper wire with ceramic insulation. The aluminum bars were 1/8" thick x 1/2" wide x 24" long. One bar was notched, as shown in Configuration A of Figure 15. An aluminum tube was then split and welded to the sensing bar. The other bar was instrumented with a surface set of transceivers as shown in Configuration B.

To check the attenuation properties of a shear wave traveling along the surface of a metal bar, a series of tests were run in liquid nitrogen.

The device illustrated in Figure 15 was submerged in a dewar of LN₂ which was placed on a scale. The signal received was then correlated to percentage of the bar in intimate contact with LN₂. This measurement was obtained by determining the amount (by weight) of LN₂ required to cover 22 inches of the sensing bar, and removing approximately 15% of the liquid for each reading.

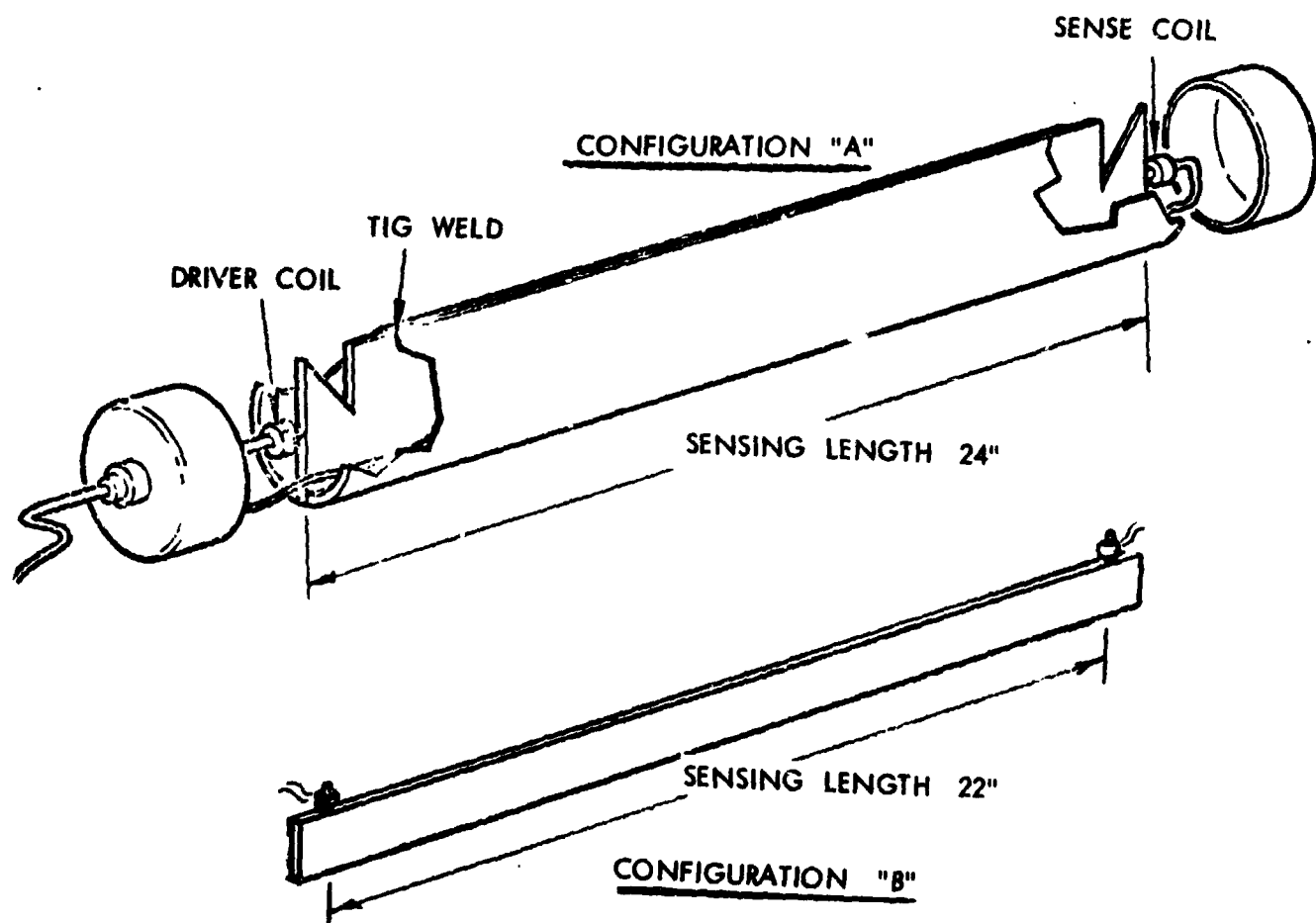


Figure 15. Ultrasonic Liquid Level Detector

The experimental data are shown in Figure 16. Figure 17 is a block diagram of the laboratory test set-up used during the tests.

The test data of Figure 16 indicate that the ultrasonic probe behaved as was predicted by theory and with little development work could be developed into a useful liquid level gauge for propellant gauging applications.

3.3.5 Light Attenuation

Several schemes using light attenuation have been considered. The optical properties of LOX and LH₂ are such that some form of coloration would need to be added. Since the color determines the amount of absorption; the coherence of the mixture must be very rigid. The difficulty of stabilizing the fuel color with respect to age, composition, and temperature history of the propellant make the light measurement extremely difficult. When considering the problems of maintaining optical parts and hardware required for this type of measurement, it appears that no obvious advantages can be gained. It is felt that the constant of proportionality could not be held stable as

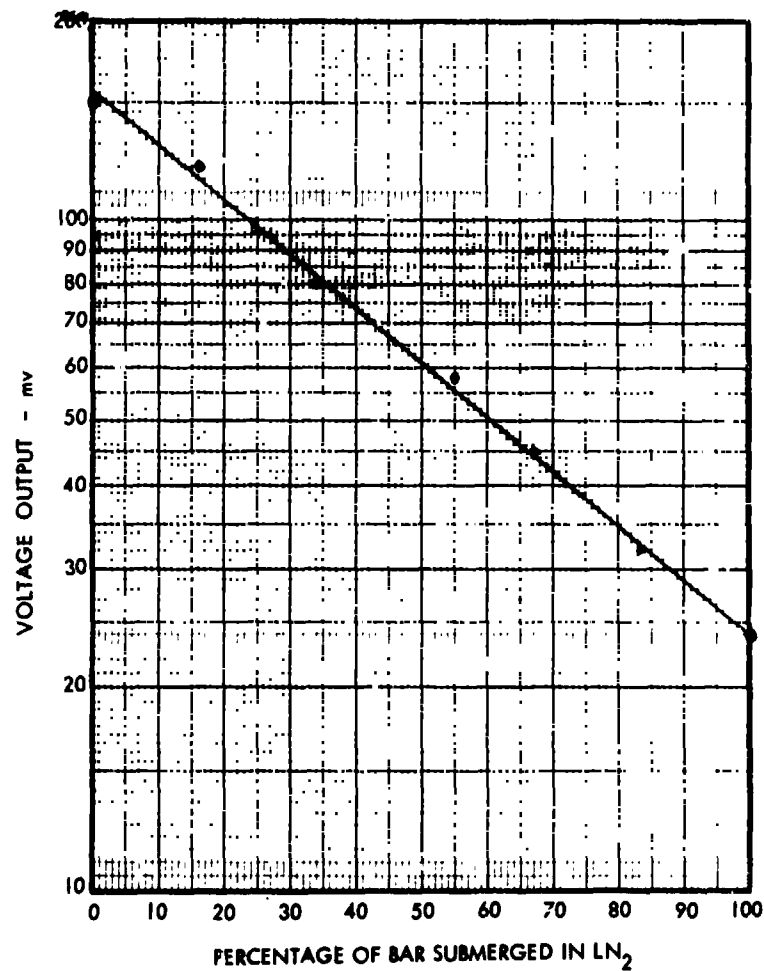


Figure 16. Calibration Curve in LN₂

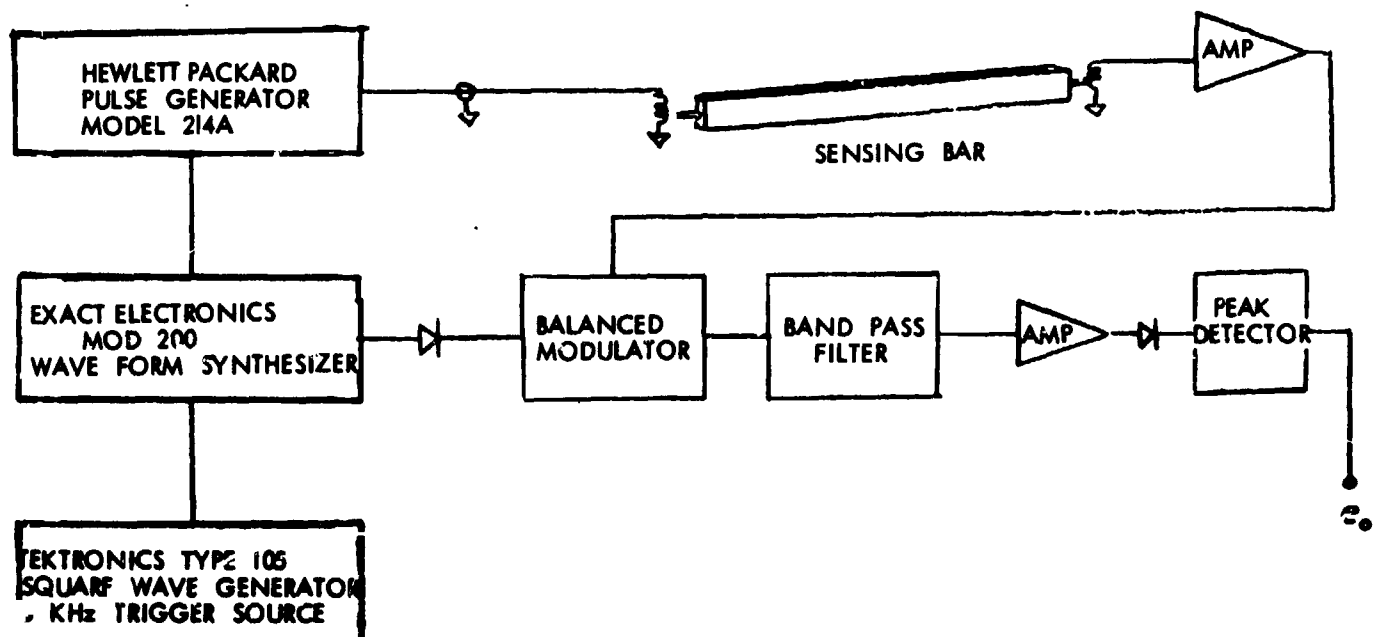


Figure 17. Block Diagram of Electronics

the mass of fuel shifted over light sources in a random manner and secondary effects such as wall temperature would affect optical alignment of reflectors or detectors and give erroneous indications of fuel quantity.

Since the optical schemes investigated have shown stringent practical limitations, no further effort was indicated.

3.3.6 Titration - Radioactive and Inert Gas

The requirement for a "Status Quo" measurement of fuel quantity severely limits any method which measures the concentration of a trace gas in the ullage. A measure of induced tracer concentration in the remaining pressurant offers a method of determining the amount of pressurant used, and by use of mass spectrometry, a very accurate measurement can be made. The requirement for a measure of useable liquid remaining precludes any consideration of ullage tracer concentration, since accumulative errors present in total venting exceed the overall accuracy requirement of the system. The use of helium as the pressurant eliminates it as a trace gas candidate, and the temperatures involved with LH_2 eliminate other potential gasses because of solidification of the tracer.

By adding radioactive tracers to the liquid propellant, the positioning of the fuel, with respect to the detector, becomes critical. Measurement of the total radiation from the tracer through the surface of the tank cannot eliminate the problem of radiation absorption within the volume of the fuel itself. Since the position and shape of the fuel configuration must be known to accurately interpret total received radiations with respect to fuel quantity, the technique offers no apparent advantages.

3.3.7 Capacitance Gauging

The tank geometry listed in Figures 2 and 3 are complex, when considering a capacitance system. The measurement requires a sophisticated voltage leveling scheme on the segmented capacitance plates.

There will be sizeable temperature gradients in the tank wall and ullage vapor. The work reported by Transonics has led us to conclude that the system fabrication would be difficult and the variation in plate capacitance as a function of wall temperature must be considered. For these reasons, the capacitance gauging scheme has been set aside for this phase of the study.

3.4 PROPELLANT POSITIONING

3.4.1 Acoustic Pumping

Acoustical pumping for the positioning of cryogenic liquids under zero g conditions has been the subject of considerable discussion. Some authors seem overly enthusiastic in their predictions for the system's performance. An example is the article by P. Wessels*. In this article, the model of motion is a constant acoustic acceleration force opposed only by the inertial mass of the hydrogen. The efficiencies claimed in the system are extremely high. The potential offered by acoustic pumping is attractive, however, to establish the efficiencies attainable needs more detailed analysis. As a beginning step in this direction we have considered a model which deals directly with the actual force producing mechanism at the liquid surface.

The model consists of a plane liquid surface with the sound wave applied through the gas-vapor in contact with the surface. The kinetic theory of gases is used to give a statistical description of the velocities of the molecules arriving and departing from the surface in terms of the instantaneous temperature of the liquid surface and the temperature of the gas throughout the sound wave cycle. From the molecules velocities, the force on the surface is then computed using the principle of conservation of momentum. (Just as the thrust of a rocket is computed).

An interesting result for a special case has been derived. The special case is where the effect of the acoustic signal is solely to create an additional vaporization of molecules at the liquid surface. For this case, the force (thrust) per watt has been calculated.

*AIAA Lecture Series, Low Gravity Propellant Orientation and Expulsion, Vol. 6, 1968, pp. 37-40.

The special case is applicable to another potential method of propellant orientation, namely, infrared pumping. In this system a source of infrared radiation is located at one end of the tank and shines upon the propellant inside the tank. Vaporization occurring at the illuminated liquid surface gives a thrust which drives the liquid to the far end of the tank. It is assumed that the absorption of infrared takes place so near the surface that a significant fraction of the energy results in vaporization on the incident side, rather than heating the liquid as a whole.

The results of the special case analysis, whether for acoustic energy or infrared energy are as follows:

Let W denote the power (watts) which actually goes into vaporization. The molecules which evaporate leave the surface with a velocity that can be specified in terms of the temperature. From this velocity and the number of molecules leaving per second, the thrust F is computed. The number of molecules evaporated per second is obtained from the heat of vaporization of the liquid and the power W .

The preliminary calculation has yielded the following results:

<u>Material</u>	<u>Temp.</u>	<u>Specific Thrust in Newtons/Watt</u>
H ₂ O	373°K	1.5×10^{-4}
LOX	90°K	5.7×10^{-4}
LH ₂	21°K	5.3×10^{-4}

To gain an intuitive feel for the meaning of these numbers, we apply the result for oxygen to a 38,000 lb. mass to be moved 15 feet by 10 watts of vaporization energy. Assuming, as other authors have done, that inertia is the only opposing force, the result is that it takes 1.45 hours for this mass to be moved. It should be restressed that to obtain 10 watts of actual vaporization may require many times this amount of power from the source.

Although the acoustic and infrared pumping appear to offer a means of propellant positioning, further analysis of these systems has been abandoned in favor of a more promising "sprinkler" destratification system described in the next section.

3.4.2 Destratification by Spraying

Liquid droplets, when absorbed by a liquid mass will transfer their momentum into the larger mass thus causing a net force in the larger mass. In this case, it is assumed that the process is essentially inelastic, since the liquid droplets are the same material as the larger mass, and the velocity of the droplet is comparatively low. By drawing liquid hydrogen or liquid oxygen from an appropriate position in the propellant cycle and accelerating it through a sprayer which directs the accelerated droplets toward the remaining fluid, preferential positioning can be theoretically achieved.

As estimate of the energy required to orient liquid propellant in zero-g can be simply made by calculating the energy required to move the mass of propellant from one location to another and estimating an efficiency for the sprayer system required to perform the process. The distance a mass will move under a constant acceleration, a , in time, t , is given by:

$$S = \frac{1}{2} a t^2$$

The acceleration of the propellant is given by the ratio of the force, F , to the propellant mass, M_p .

$$a = \frac{F}{M_p}$$

Solving for F gives:

$$F = \frac{2 s M_p}{t^2}$$

Utilizing a LH_2 tank with 7 feet hemispherical ends and a 6 feet central cylindrical section, the mass of LH_2 propellant for 2/3, 1/2, and 1/3 tank full conditions was calculated for a propellant density of 0.07 gm/cm^3 . Assuming that the propellant was located at the end of the tank nearest the sprayer (maximizing the energy required), the distance that the centroid of the propellant mass must be moved was estimated:

Propellant Motion Results

<u>Tank Conditions</u>	<u>Propellant Mass, gms</u>	<u>Centroid Motion, cm</u>
Full	4.67×10^6	0
2/3 Full	3.12×10^6	183 (~6 ft)
1/2 Full	2.34×10^6	244 (~8 ft)
1/3 Full	1.56×10^6	365 (~12 ft)

Substituting the above results in the force equation facilitates calculation of the force required to orient the propellant. The work or energy required is merely the product of the force and the distance:

$$E = \frac{2 s^2 M_p}{t^2}$$

The power required is the time rate of doing work:

$$P = \frac{2 s^2 M_p}{t^3}$$

Sample data for a reorientation time of 10 minutes are shown below. Figure 18 shows the power and energy requirements as a function of time for various tank conditions.

Data for an Orientation Time of 10 Minutes

<u>Tank Conditions</u>	<u>Force, dynes</u>	<u>Energy, ergs</u>	<u>Power, ergs/sec</u>
2/3 Full	3180	5.8×10^5	9.67×10^2
1/2 Full	3180	7.8×10^5	1.3×10^3
1/3 Full	3180	1.16×10^6	1.93×10^3

It is noted that the energy required increases with a decrease in time because a larger force is applied through a given distance. The velocity of the propellant when it reaches the far end of the tank is correspondingly higher, however, due to the relation between impulse and momentum:

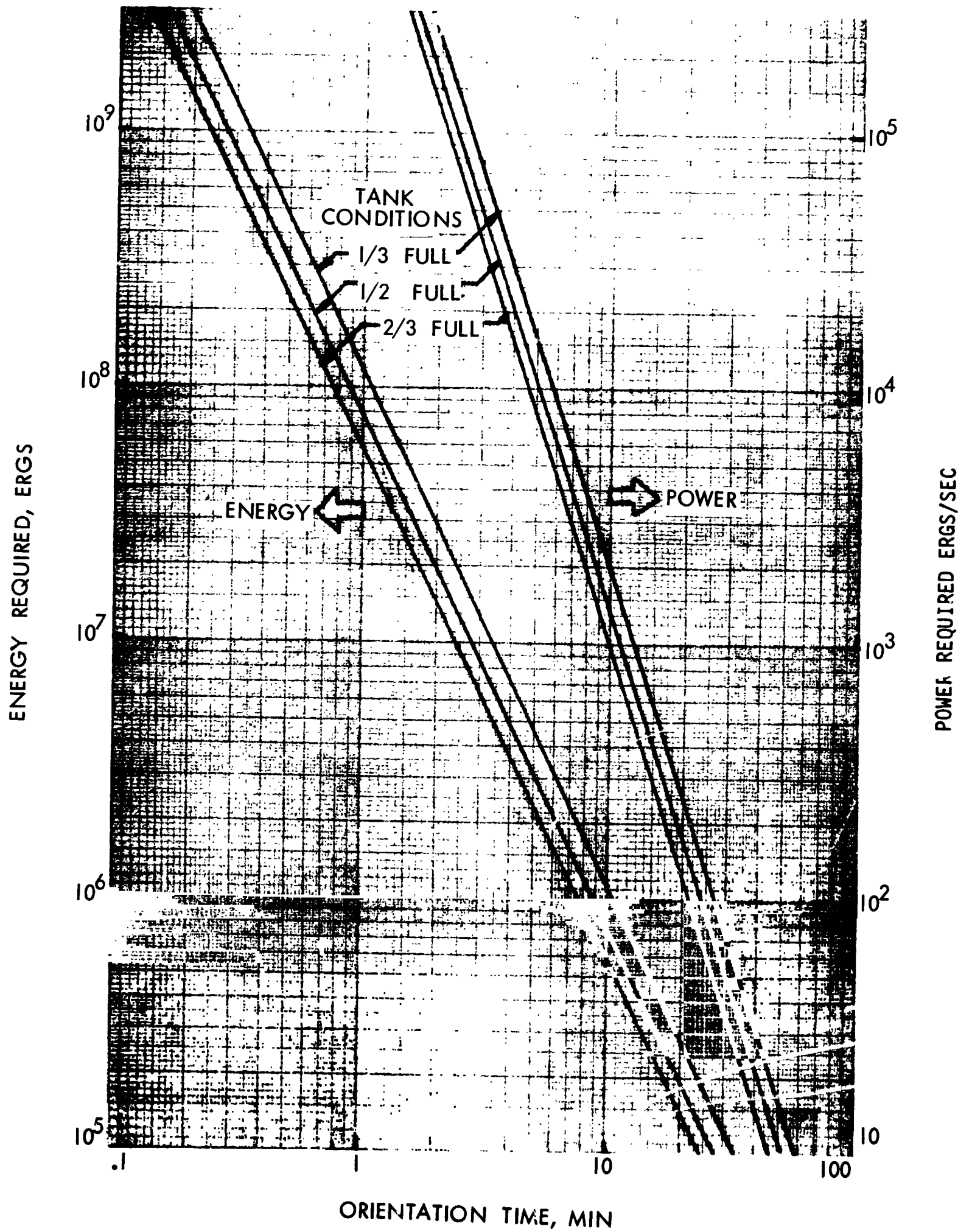


Figure 18. Minimum Power and Energy Requirement for Destratification of LH_2 in Zero-G

$$F \Delta t = M_p \Delta V$$

$$\text{or } \frac{2 s M_p}{\Delta t^2} \Delta t = M_p \Delta V \text{ and } V_{\text{final}} = V_{\text{initial}} + \frac{2 s}{\Delta t}$$

Inherent in all of the above results is the assumption that a constant force is exerted during the entire time that the propellant is migrating to the far end of the tank.

Figure 18 shows the power or energy required if the process is 100% efficient. Steam turbines can achieve efficiencies of as high as 90%. Water jets on moving blades can achieve efficiencies of as high as 50% (ratio of the energy given to the blade to the energy in the jet). It appears that efficiencies anywhere from a few to thirty percent might be achieved. In any event, estimates of efficiency can be made and the data in Figure 18 used to determine the input power required. For example, if ten percent efficiency is assumed along with an orientation time of 10 minutes, the input power required is only 2 milliwatts (2×10^4 ergs/sec).

4.0 SUMMARY OF GAUGING SYSTEMS AND HOW THEY APPLY TO SHUTTLE VEHICLE TANKS

From the proceeding discussion it is possible to make up a summary table, shown in Table 4-1 which relates tank configuration, "g" conditions and the possible gauging systems that could be used.

The table indicates that the only practical way to gauging LH₂ in true zero-g conditions is Nuclear (and possibly RF). In tanks which contain surface tension devices, nuclear means are the only known way to gauge the propellant quantity (it is assumed that RF will not work in a tank which contains numerous baffles and screens).

Table 4-1. Summary of Gauging System

	<u>True Zero-g</u>	<u>Propellant Settling</u>
LH ₂ TANKS		
Tank without Screens	Nuclear (RF)	Nuclear (RF) Level Measurement
Tank with Screens	Nuclear	Nuclear Level Measurement
LO ₂ TANKS		
Tank without Screens	Nuclear RIGS (RF ?)	Nuclear RIGS Level Measurement (RF ?)
Tank with Screens	Nuclear RIGS	Nuclear RIGS Level Measurement

If propellant settling techniques are employed, liquid level gauges can be used such as capacitance or TRW's ultrasonic probe. Of course, liquid settling will also simplify the nuclear gauge by significantly reducing the required number of source-detector pairs.

C

For LOX, the RIGS and nuclear methods appear capable of performing the gauging function. However, as the tank gets large (~10 ft. diameter) the nuclear systems starts losing its advantages because the gamma rays are excessively attenuated by the fuel and the requisite source strengths become too large to be practical. RIGS, on the other hand, becomes more attractive as the tank size increases. For large tanks the resonating frequency should be low so that the system becomes less sensitive to variations of ullage gas and the presence of surface tension screens.

Referring to Table 4-1, it is seen that between the nuclear and the RIGS gauges most gauging conditions can be satisfied. However, since the RIGS can not operate properly during engine firing, it should be supplemented by a liquid level measurement such as a capacitance or ultrasonic gauge.

The nuclear gauge is currently under development sponsored by the Air Force with interest from NASA/Houston. However, development of RIGS would provide a very attractive means of gauging LOX in large tanks under zero-g conditions.

Also development of TRW's Ultrasonic Gauge and/or incorporating a capacitance probe would provide means of measuring the propellant quantity during engine burn conditions or in conjunction with liquid positioning devices.

4.1 RECOMMENDATIONS

Based on the preceeding discussions, the following recommendations are made:

1. Pursue the RIGS concept for gauging of LOX. The program should consist of:
 - a. Tests to select the final diaphragm material for an isothermal RIGS.
 - b. Construction of a breadboard RIGS sensor and performance of lab tests to determine the frequency required to operate the system in an isothermal mode. Also tests to determine the frequency requirements where the RIGS can gauge tanks containing surface tension screens should be performed.
 - c. After completing the RIGS breadboard test, a complete gauging system should be designed for demonstration in large tanks such as SIVB LOX tanks or Shuttle LOX tanks, if it becomes available.

2. Develop the ultrasonic liquid level sensor to augment RIGS during the time the engine is on and where RIGS is not operational or for use with liquid positioning devices.
3. Since propellant destratification will help and/or simplify the operation of virtually any gauging system that may be selected, pursue the development of the sprinkler for propellant positioning under zero-g.
4. Establish a test program to test the RIGS, ultrasonic liquid level gauge and the sprinkler concept in:
 - Small tanks under simulated zero-g such as using the KC-135 zero-g aircraft.
 - Large cryogenic tanks such as SIVB and/or actual Shuttle Vehicle tanks under 1-g conditions to check full size system operation (RIGS & Ultrasonic Liquid Level Gauges).

A flow diagram of the overall program required to develop systems for gauging Shuttle Vehicle tanks under zero-g conditions (with exception of the Nuclear and RF gauges which are already under development) is given in Figure 19.

The work statements for Task 3 and 4 outlined in Figure 18 have been submitted to NASA/MSFC in TRW Proposal No. 16878.003, "Destratification Tests in Zero-G."

As shown in Figure 18 successful completion of Task 1, 2, 3 and 4 should be followed by Task 5, Systems Tests. These tests will verify that the gauging system and the sprinkler system are operating properly. It is recommended that two sets of tests be performed:

1. Tests in a small tank under simulated zero-g conditions such as using the KC-135 zero-g aircraft operated by the USAF at Wright-Patterson Air Force Base.
2. Tests in a large tank using LOX and/or LH₂ such as using SIVB stage or real shuttle tanks when they become available at that time.

Tests in small tanks will provide the required confidence level that the RIGS, the ultrasonic probe, and the sprinkler system are capable of operating under zero-g. Tests in large tanks will provide a complete full size system checkout for RIGS and the ultrasonic liquid level gauge.

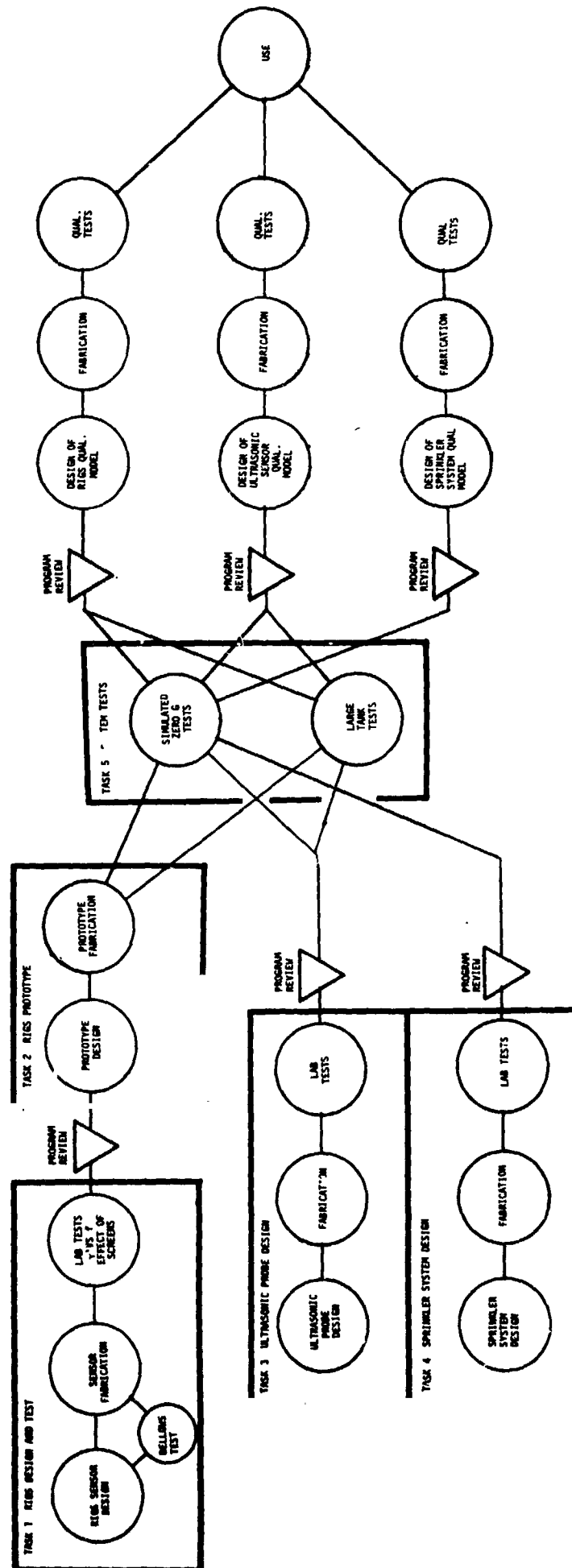


Figure 19 Flow Diagram of the Propellant Gauging Development Program for the Shuttle Vehicle

APPENDIX A

Table A-1

PHYSICAL PROPERTIES OF OXYGEN AND HYDROGEN

	<u>Oxygen</u>	<u>Hydrogen</u>
Molecular Weight	32.0	2.016
Z Number	8	1
Gas Constant (R)	48.3	767
NBP	162°R	37.8°R
Triple Point	108°R	25.3°R
Liquid Density	71.3#/ft ³	4.4#/ft ³
Vapor Density	.29#/ft ³	.083#/ft ³
Viscosity @NBP	.195 Centipoise	12 Micropoise
Specific Heat Ratio cp/cv	1.40	1.40
Surface Tension @NBP	1.91×10^{-4} #/m ²	2.76×10^{-5} #/in ²
Dielectric Constant ϵ	1.507 @ 108°R	1.223 @ 36°R
Ionization Potential	13.55	13.53
Magnetic Moment μ	-1.89	+2.79
Refractive Index (m_μ)	1.221 @ 108°R	1.114 @ 36°R
ν Attenuation (662 kev X-Section, Liquid Half Thickness)	3.1 inches	25 inches
Thermal Conductivity k/k ₀	.406 @ 198°R	.136 @ 36°R
Sound Velocity	3710 ft/sec @ 108°R	3680 ft/sec @ 36°R
Compressibility Z	.99978 @ 108°R	.9991 @ 36°R

APPENDIX A

Table A-2

DESIGN PARAMETERS

PROPELLANTS	LH ₂	LOX
VENT PRESSURE	~ 2ATM	~ 2ATM
TANK CAPACITIES-(MAIN)	~ 16,230 ft ³	~ 6,010 ft ³
	~ 2,115 ft ³	~ 516 ft ³
TANK GEOMETRIES	Cylindrical with hemospherical end caps	
FLUID TEMPERATURES	13.869°K to 54.9°K to 22.861°K (NBP) 90.2°K (NBP)	
SYSTEM ACCURACY	2%	2%
MISSION DURATION	~ 7 Days	~ 7 Days
VEHICLE USAGE	~ 100 Flights	~ 100 Flights
TANK INSULATION	Yes - Au-Kapton	Yes - Au-Kapton
TANK MATERIAL	Aluminum Alloy	Aluminum Alloy
ULLAGE	H ₂	He+O ₂

APPENDIX B

Several brainstorming sessions were held in which a number of specialists were invited. The purpose was to efficiently use in-house technical specialists to consider novel approaches. Follow-up of several small group sessions was then implemented. Particular emphasis was placed on a new method of zero-g gauging. From these sessions have evolved the particular emphasis in this report on acoustic techniques. It appears that by combining several characteristics, i.e., acoustic pumping, and ultrasonics, that a workable measurement system will evolve.

Table B below lists some of the participants and consultants used in this effort.

Table B

Haefl, A. V.	Ph.D	Electronics, Acoustics
Johnson, R. L.	Ph.D	Lasers, Holography
Jones, I. R.	Ph.D	Nuclear Systems
Kaminskas, R. A.	B.S.	Radiation Measurements
Knox, Cameron	Ph.D	Lasers, Acoustics
McGrath, E. J.	Ph.D	Physics
O'Neill, J. P.	B.S.	Acoustics, Liquid Sloshing
Salvinski, R. J.	M.S.	Noise Analysis, Measurement Systems
Zivi, S. M.	M.S.	Lasers, Thermodynamics

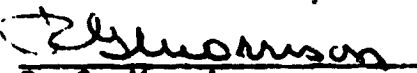
Quarterly Progress Report #3


Propellant Quantity Gauging System Under Zero G

NASA George C. Marshall Space Center

Contract NAS 8-26116

December 11, 1970 through March 10, 1971

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QUARTERLY PROGRESS REPORT No. 3

PROPELLANT QUANTITY BY GAUGING SYSTEM UNDER ZERO-G

This report summarizes the work performed on the Propellant Quantity Gauging System under zero-g performed for NASA-MSFC for the period December 11, 1970 through March 10, 1971.

Six monthly and two quarterly reports have been issued on this contract.

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1.0 INTRODUCTION

This is the third quarterly report of a one-year study contract being conducted to analyze and evaluate existing state-of-the-art in zero-g propellant quantity instrumentation. Emphasis has been placed on the origination of new concepts, and identification of key problem areas in candidate systems. Detailed consideration of the RF gauging system is excluded from this study.

2.0 REVIEW OF PREVIOUS QUARTER

Three systems were identified as having potential to meet the zero-g gauging requirements.

These systems are nuclear attenuation, resonant infrasonic, and ultrasonic attenuation.

Problems identified with each technique are as follows:

Nuclear Attenuation. The use of source-detector pairs for measuring density is limited to low density propellants because of the source strength required to penetrate a given thickness of fuel. The personnel exposure limit is 10 mr/hr at one foot. Since the LOX system would require sources capable of penetration distances of approximately eighty inches of dense liquid, the nuclear technique is not considered feasible. For LH_2 , however, the nuclear system is considered a leading candidate, provided a representative temperature of the ullage vapor or LH_2 can be obtained. This temperature measurement is required to determine the molecular ratio of gas/liquid between a given source detector pair.

Resonant Infrasonic Gauging System. This system determines the ratio of compressibilities between two known volumes; i.e., a reference volume and an empty tank volume. By establishing a resonance between the reference volume and the ullage volume (with respect to the original tank volume), a measure of ullage volume can be obtained. Since the compressibility of the two vapor volumes is the basic measurement, the liquid being monitored must have very little compressibility, and the specific heat ratio must be known accurately. In LH_2 , vapor properties such as specific heat change rapidly

with temperature. In addition, the LH_2 has a relatively high degree of compressibility. A temperature sensitivity analysis was conducted which indicated that unless the ullage temperature was known to better than 1°R , the measurement accuracy of the RIGS system would not meet the accuracy goal of 2%. Of further concern was that the absolute accuracy decreased as the LH_2 volume decreased. For these reasons, RIGS is considered undesirable for gauging LH_2 .

For LOX, the two major variables (compressibility of LOX and specific heat ratio) are within the limits required for gauging accuracy. The significant problem identified is in keeping liquid away from the weighted diaphragm of the resonant element. This can be accomplished by placing an isolation diaphragm between the weighted diaphragm and main tank, provided the area of the isolation diaphragm is at least an order of magnitude greater than the weighted diaphragm and can be made flexible enough to not add significant impedance to the system.

Ultrasonic Attenuation. Since the ultrasonic system is dependent on liquid being in contact with the sensor, further consideration was set aside during the second quarter activities. A preliminary analysis of the power required to preferentially position the liquid by means of sprinklers or spraying systems was undertaken. If a system can be designed that will position the ullage bubble, the ultrasonic gauging method becomes a leading candidate for both LOX and LH_2 .

3.0 THIRD QUARTER ACTIVITIES

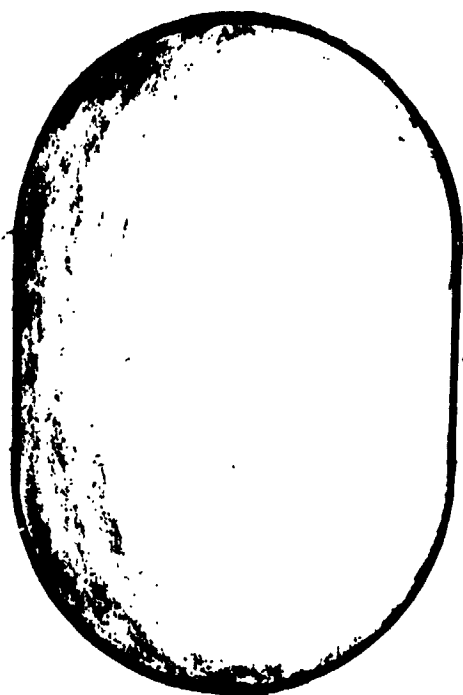
3.1 Current Tank Configurations

NAR and MDC, Phase II Space Shuttle Study contractors, furnished the current tank geometries illustrated in Figures 1 and 2. The zero-g gauging requirements is limited to Auxiliary Propulsion System tanks on the orbiter vehicle.

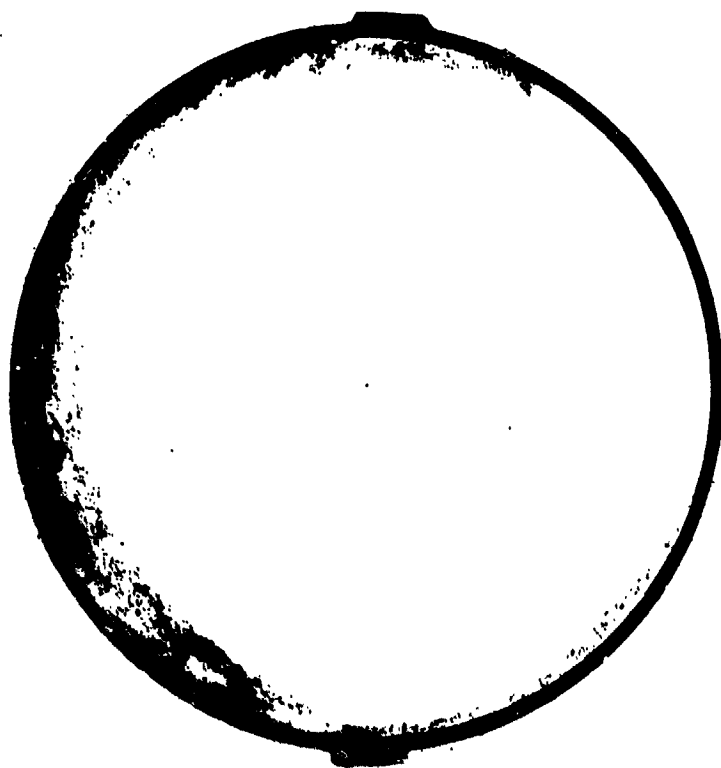
3.2 Specific Systems

3.2.1 Nuclear Attenuation Gauging

The zero-g nuclear fuel gauge consists of a set of source detector pairs with the radiation from each source being measured by its corresponding detector



LOX APS TANK
7.2' DIAM.
278 FT³
2 REQUIRED



LH₂ APS TANK
11.6' DIAM.
825 FT³
2 REQUIRED

FIGURE 1. NAR APS TANKS

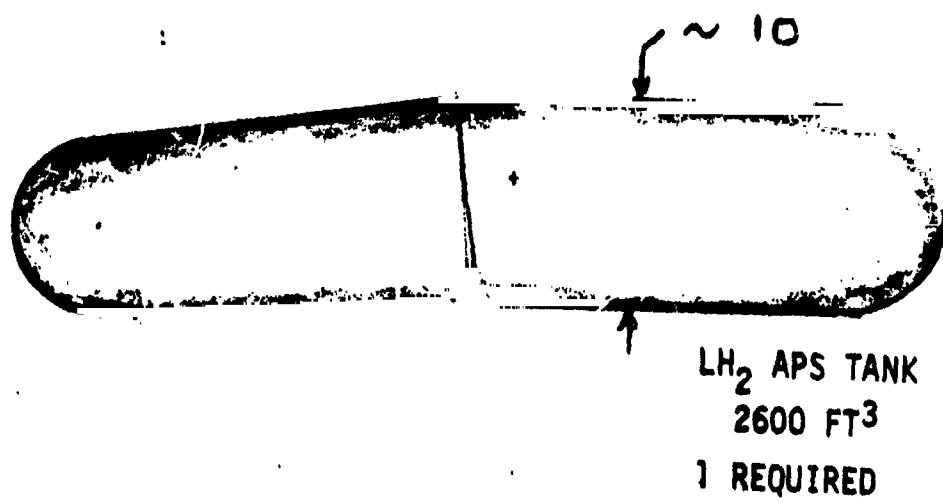
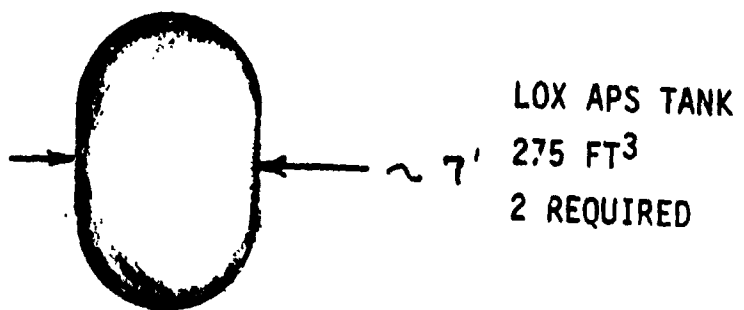


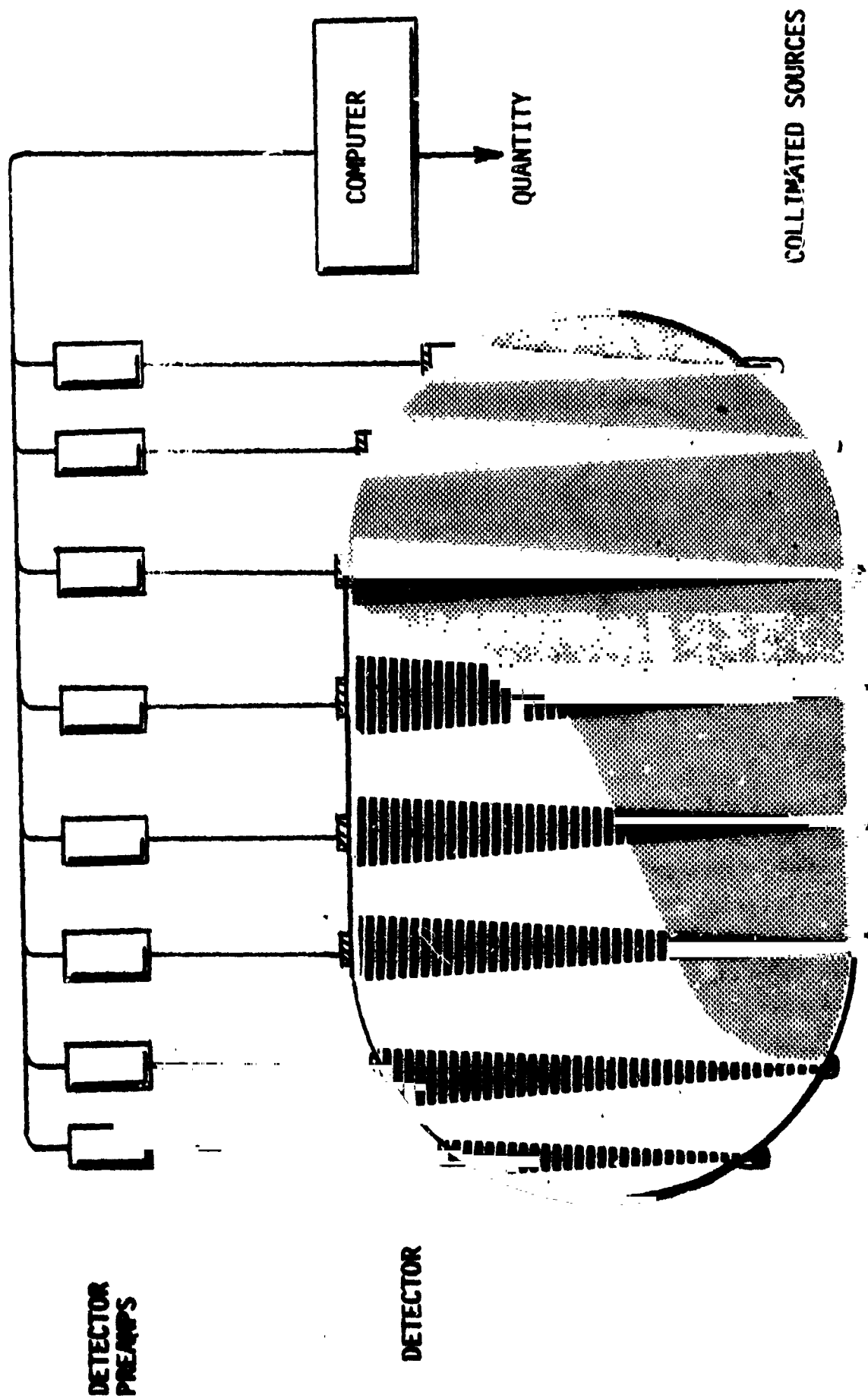
FIGURE 2. MDC APS TANKS

only (Figure 3.) The geometry chosen for the initial analysis is illustrated in Figure 4. This geometry was chosen from MDC concepts presented last quarter. Any fuel between a source-detector pair will attenuate the radiation from the source and this attenuation may be related directly to the fuel thickness between a source-detector pair. Taken as a two-dimensional array, all of the measured fuel thickness with their corresponding locations describe a surface which bounds a three-dimensional volume. Integration over this surface results in a value for the volume of fuel present. The term "fuel" in this analysis refers to total quantity of hydrogen, gaseous and liquid. The nuclear gauge measures mass between a source and detector independent of phase. To discriminate between phases requires an independent temperature measurement.

A comprehensive analysis of the measurement error due to random fuel orientation under zero-g conditions was undertaken. The conditions established were a "worst case" assumption; i.e., that no knowledge of fuel position was available and that the void would be comprised of many random bubbles between any source/detector pair.

The primary effort in the error analysis consisted of development of a computer code (GAGE) which calculates the required error distribution functions for any set of source-detector pairs and any particular fuel loading for a specified tank geometry. The mechanics of the code, the relationship of the calculated error distributions to the nuclear gauge fuel measurements and the resultant measurement error as a function of the number of source-detector pairs and fuel loading were developed to generate worst case conditions.

Under zero-g conditions, the fuel in the tank (for any fuel loading) will assume some unknown orientation and shape in the tank. Since the surface seen by the source-detector pairs will vary with fuel orientation, the value of the integration for a particular fuel loading and a given number of source-detector pairs will vary with the fuel orientation. If the fuel orientation in the tank under zero-g conditions is assumed to have certain constraints (i.e., the void volume consists of a random number of randomly placed spherical bubbles in the tank), for a particular fuel loading a large number of separate measurements of the fuel (each with a different fuel orientation) will form a distribution of measured fuel volume values for the particular fuel loading. These distributions are referred to as error distribution functions since they describe the behavior of the measurement error.



NUCLEAR ATTENUATION GAUGE

FIGURE 3

The amount of variation in the distribution of measured values described by an error distribution function for a particular fuel loading and a given number of source-detector pairs may be directly related to the "absolute error"*. The amount of variation in a distribution is characterized by the standard deviation which is defined by equation 1).

$$\sigma = (\sum_n (x_n - \bar{x})^2 / N)^{1/2} \quad 1)$$

where: σ = Standard deviation
 x_n = The n^{th} value of the sample
 \bar{x} = Mean value of the sample
 N = Number of samples

For a normal distribution there is a 68% probability that any single measurement will fall within \pm one standard deviation of the mean of the distribution. The standard deviation may be used to obtain percent absolute error by using equation 2):

$$E_a = 100 \sigma / T_f \quad 2)$$

where: E_a = Percent absolute error
 σ = Standard deviation as a function of given tank geometry
 T_f = Full tank volume

In the analysis here the full tank volume was normalized to 1, therefore $T_f = 1$ and equation 2) becomes:

$$E_a = 100 \sigma \quad 3)$$

Hence, the standard deviation value of the error distribution functions represent the decimal equivalent of the percent absolute error values.

* "Absolute error" refers to the percent error in the measurement based on the full tank volume.

GAGE was written to perform the tedious calculations needed to determine the required error distribution functions. The code was written assuming perfectly collimated source-detector pairs and assuming that the void volume in the tank could be approximated by a random number of randomly sized spherical bubbles. A subroutine was developed which selects random bubble sizes and locations in the tank, constrained such that the bubbles do not overlap and that their total volume is equal to some desired void volume. This subroutine was used to generate a large number of different "bubble configurations", each corresponding to a particular void volume. A second subroutine was developed to calculate the fuel thicknesses seen by a set of source-detector pairs for each bubble configuration generated. A third subroutine was used to integrate over the surface described by each set of fuel thicknesses. The main routine in the code groups the calculated fuel volume values in a distribution which is the desired error distribution function and calculates the standard deviation for the distribution.

The logic in the subroutine which selects the random bubble configurations is set up such that it first selects the coordinates of a bubble and then the radius. After the first bubble is selected for a particular bubble configuration the coordinates of any following bubble in the configuration are selected at random until a set of coordinates are found which lie outside of any previously selected bubbles. The radius is then picked randomly but constrained such that it does not overlap the tank walls or any previously selected bubbles. Bubbles are selected until the void fraction corresponding to the desired fuel loading is obtained. An optional bias routine is included in the bubble generator subroutine which permits selecting a large radius for the first bubble in a bubble configuration. This option was required in order to limit the number of bubbles needed to fill a bubble configuration for low fuel loadings. Trial computer runs indicated that the amount of computer time needed to perform the calculations with no bias would be prohibitive for low fuel loadings.

The integrations were performed using both Simpson's Rule integration and area weighting integration. In using Simpson's Rule, the source-detector pairs were arranged in evenly spaced rows with evenly spaced source-detector pairs in each row as shown in Figure 4 for 25 source-detector pairs. The integrations

performed were actually a double integration for Simpson's Rule. First, the thicknesses in each row were integrated and then these values integrated over the number of rows. The equations for Simpson's rule integration are given in equations 4) and 5):

$$I_j = \frac{\Delta z_j}{3} \left[4 \sum_{i=1}^{m_j} t_{i,j} + 2 \sum_{k=2}^{m_j-1} t_{k,j} \right] \quad \begin{matrix} i = 1, 3, \dots, m_j \\ k = 2, 4, \dots, m_j-1 \end{matrix} \quad 4)$$

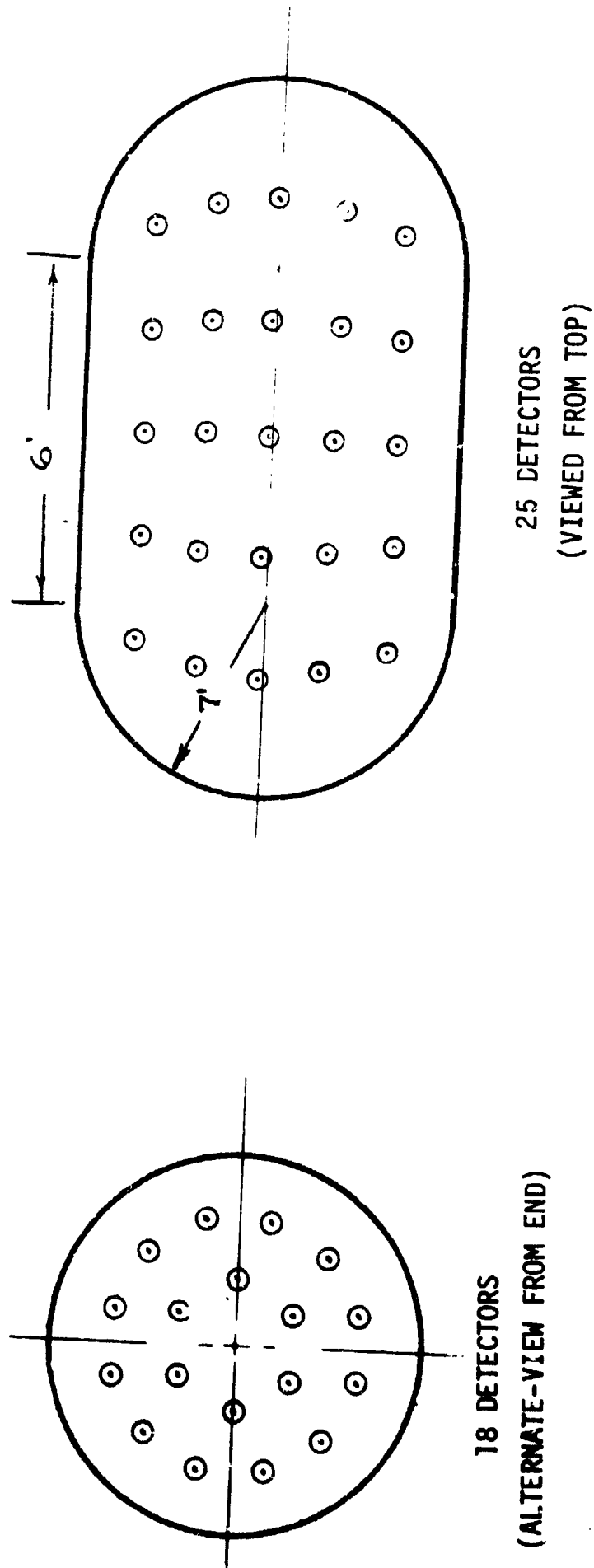
$$V = \frac{\Delta x}{2} \left[4 \sum_{j=1}^n I_j + 2 \sum_{k=2}^{n-1} I_k \right] \quad \begin{matrix} j = 1, 3, \dots, n \\ k = 2, 4, \dots, n-1 \end{matrix} \quad 5)$$

where: I_j = The integral for the j^{th} row
 Δz_j = The spacing between detectors in row j
 m_j = The number of detectors in the j^{th} row (must be odd)
 Δx = Spacing between rows
 n = Number of rows (must be odd)
 V = Volume integral
 $t_{i,j}$ = Fuel thickness for detector i in row j

The equation for the area weighting integration is given by equation 6):

$$V = \sum_i t_i A_i \quad 6)$$

where: V = Volume integral
 t_i = Thickness for source-detector pair i
 A_i = Area weight for source-detector pair i



For an end view of the tank, the source-detector requirement is scaled to the cross-sectional view area. For this particular geometry it would be the ratio of the end view area to the top view area.

LOCATION OF SOURCE-DETECTOR PAIRS

FIGURE 4

GAGE was used to generate the absolute error values presented in Tables I and II for fuel loadings of 0.1, 0.25, 0.5, and 0.75 and specific numbers of source-detector pairs of 15, 25, 51, and 99. The tank geometry used in the code for the MDC-APS liquid hydrogen tank was a six foot cylinder with radius of seven feet having two hemispherical ends each seven feet in radius. The 95% confidence intervals for each absolute error value were calculated and the corresponding values also presented in Tables I and II (Page 12). The 95% confidence interval is interpreted as meaning the interval within which the true absolute error value lies, with 95% probability. The mathematics and calculations used to arrive at the confidence interval values are detailed in Appendix A.

For each fuel loading, 400 separate bubble configurations were generated. A large number of samples were required in order to obtain adequate statistics. The average number of spherical bubbles required to fill a bubble configuration varied from approximately 15 bubbles for a tank loading of 0.75 and no bias to approximately 40 bubbles for a tank loading of 0.1 and a bias of 0.9. The bias of 0.9 means that the radius of the first bubble in each configuration generated for a tank loading of 0.1 was randomly selected such that it is between the maximum radius (which will fit in the tank) and 0.9 of the maximum radius.

The absolute error values presented in Tables I and II are plotted in Figures 5 and 6, respectively, as a function of number of source-detector pairs and fuel loading. For the worst case fuel loading of 0.1 (the greatest error for the same number of source-detector pairs) the required number of source-detector pairs as illustrated in Figure 3 for 2% accuracy are:

o Simpson's Rule Integration	62 source-detector * pairs	95% confidence interval: 52-74 source-detector pairs
o Area Weighting Integration	58 source-detector pairs	95% confidence interval: 46-68 source-detector pairs

Table I: Absolute Error (1 Standard Deviation)
For Simpson's Rule Integration*

Fuel Loading (Fraction of tank full)	No. of Source-Detector Pairs			
	15	25	51	99
0.10	4.3%±0.35%	3.3%±0.27%	2.2%±0.18%	1.6%±0.13%
0.25	3.3%±0.27%	2.6%±0.21%	1.9%±0.16%	---
0.50	3.2%±0.26%	2.4%±0.20%	1.3%±0.11%	0.8%±0.07%
0.75	2.4%±0.20%	1.9%±0.16%	0.9%±0.08%	0.5%±0.04%

*95% confidence that the absolute error values are within the stated error limits.

Table II: Absolute Error (1 Standard Deviation)
For Area Weighting*

Fuel Loading (Fraction of tank full)	No. of Source-Detector Pairs			
	15	25	51	99
0.10	3.9%±0.32%	2.8%±0.23%	2.1%±0.17%	1.5%±0.12%
0.25	2.8%±0.23%	2.0%±0.17%	1.5%±0.12%	---
0.50	2.6%±0.21%	1.9%±0.16%	1.0%±0.08%	0.6%±0.05%
0.75	2.1%±0.17%	1.6%±0.13%	0.7%±0.06%	0.4%±0.03%

*95% confidence that the absolute error values are within the stated error limits.

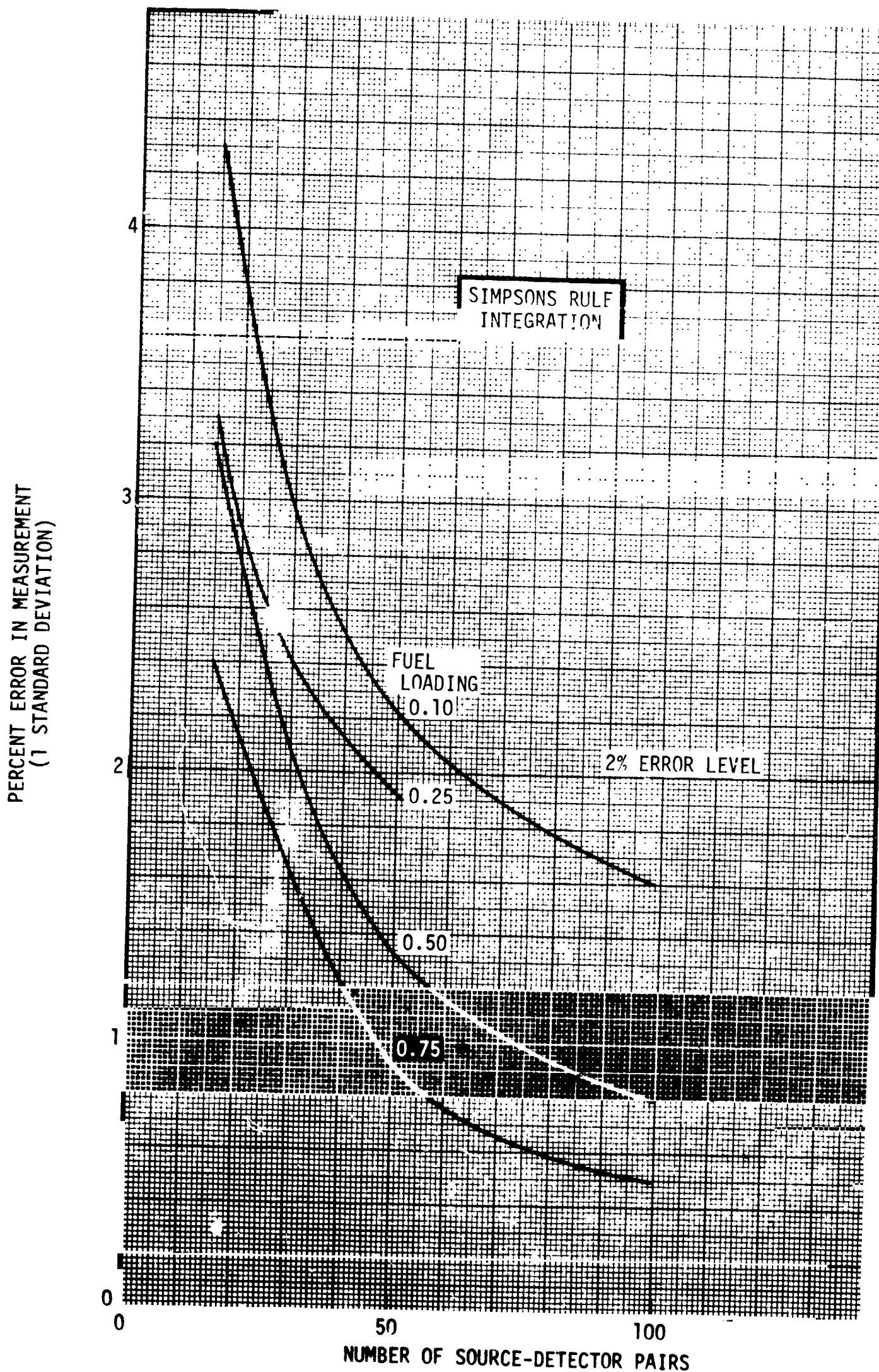


FIGURE 5. PERCENT ERROR IN FUEL MEASUREMENT FOR SIMPSON RULE INTEGRATION

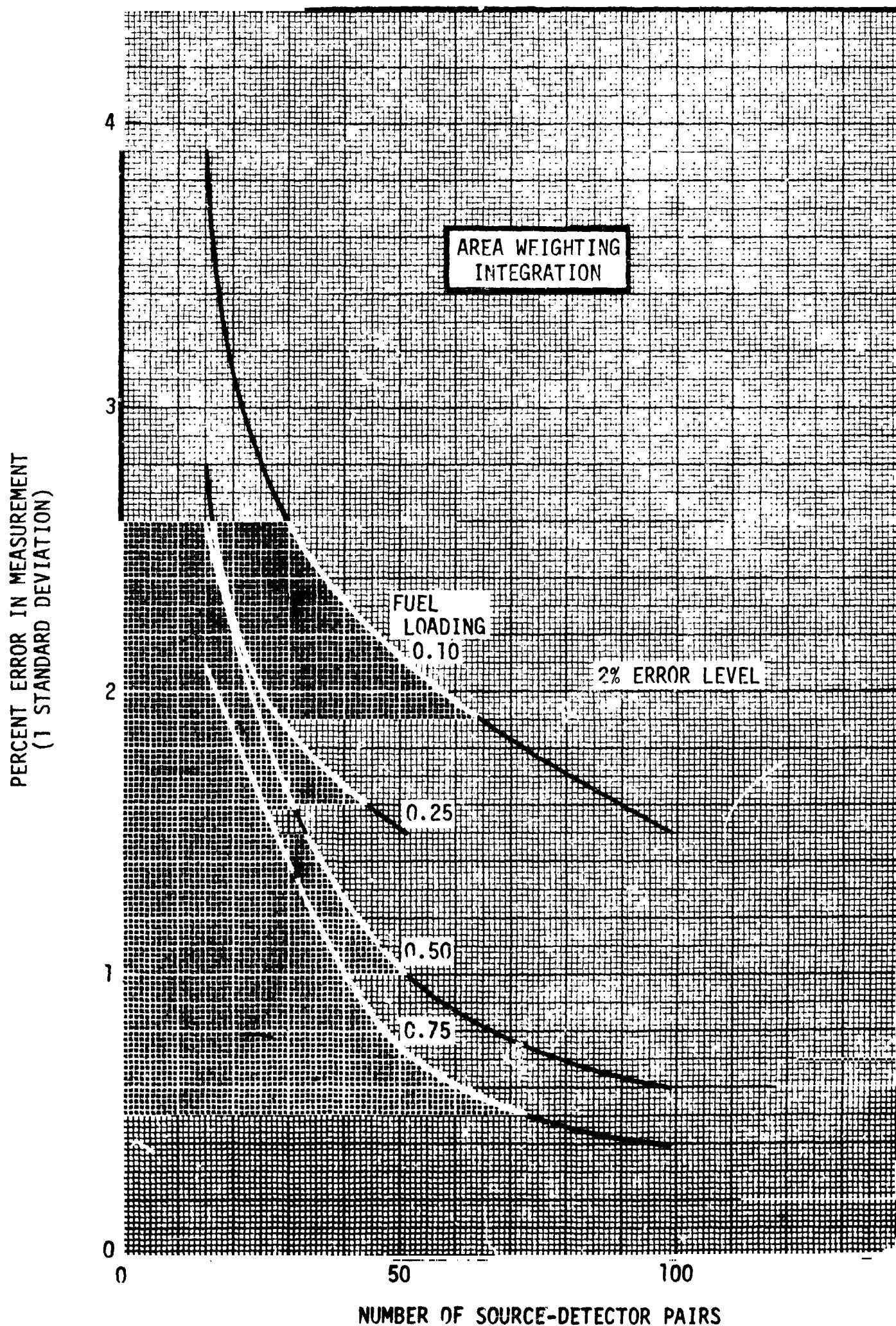


FIGURE 6. PERCENT ERROR IN FUEL MEASUREMENT FOR AREA WEIGHTING INTEGRATION

Figures 7 and 8 illustrate the error distribution functions for a fuel loading of 0.10 of tank full. Figure 7 presents the distributions for 15 and 25 source-detector pairs while Figure 8 presents the distributions for 51 and 99 source-detector pairs. The distributions are normalized to the same area under each curve. Each curve was found by drawing by hand the best fit curve through the group frequency data. As would be expected, the distribution became narrower and more peaked with increasing number of source-detector pairs. Also the distributions appear to approximate a "normal" distribution.

The NAR tank (Figure 1) would require approximately 28 source-detector pairs/tank to achieve the desired 2% accuracy.

It should be re-emphasized that this analysis shows a worst case condition; i.e., that no knowledge of fuel orientation or behavior is available. The multiple bubbles randomly located are not considered likely. A more probable situation will be a single bubble located near the most significant heat leak in the system.

Monitoring of the performance of the development of a zero-g system for the Air Force Rocket Propulsion Laboratory has continued.* Phase 1A: Evaluation of Cadmium-Telluride Detectors has been completed and a copy of Technical Report AFRPL-TR-71-5 has been sent to MSFC.

Since other development work is underway in the nuclear gauging technique, no further analysis or lab tests are anticipated on this contract. Results of the progress of that program will be summarized in a final evaluation at the conclusion of this program.

3.2.2 Resonant Infrasonic Gauging System

The LOX tank geometries shown in Figures 1 and 2 make RIGS a logical candidate for zero-g gauging. The use of twin tanks, being considered by both study contractors, actually strengthen the feasibility of the concept, since the physical size of resonant diaphragm will be compatible with known performance of stainless steel bellows in cryogenic temperatures.**

* TRW Contract F04611-71-C-0010.

** Thompson; Welded Metal Bellows, A Reliable Positive Expulsion Device for Liquid Propellants.

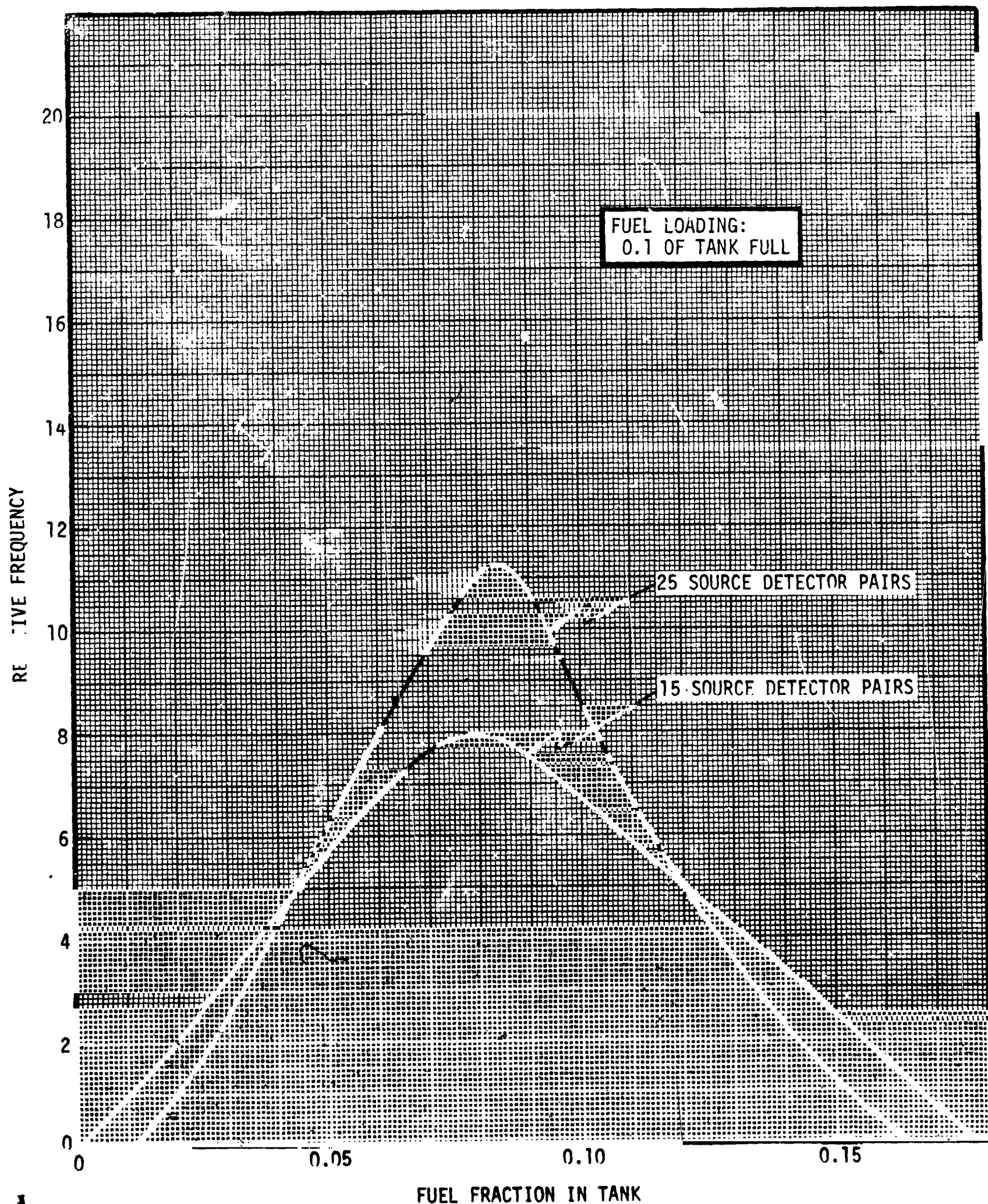


FIGURE 7. ERROR DISTRIBUTION FUNCTIONS FOR 15 AND 25 SOURCE DETECTOR PAIRS

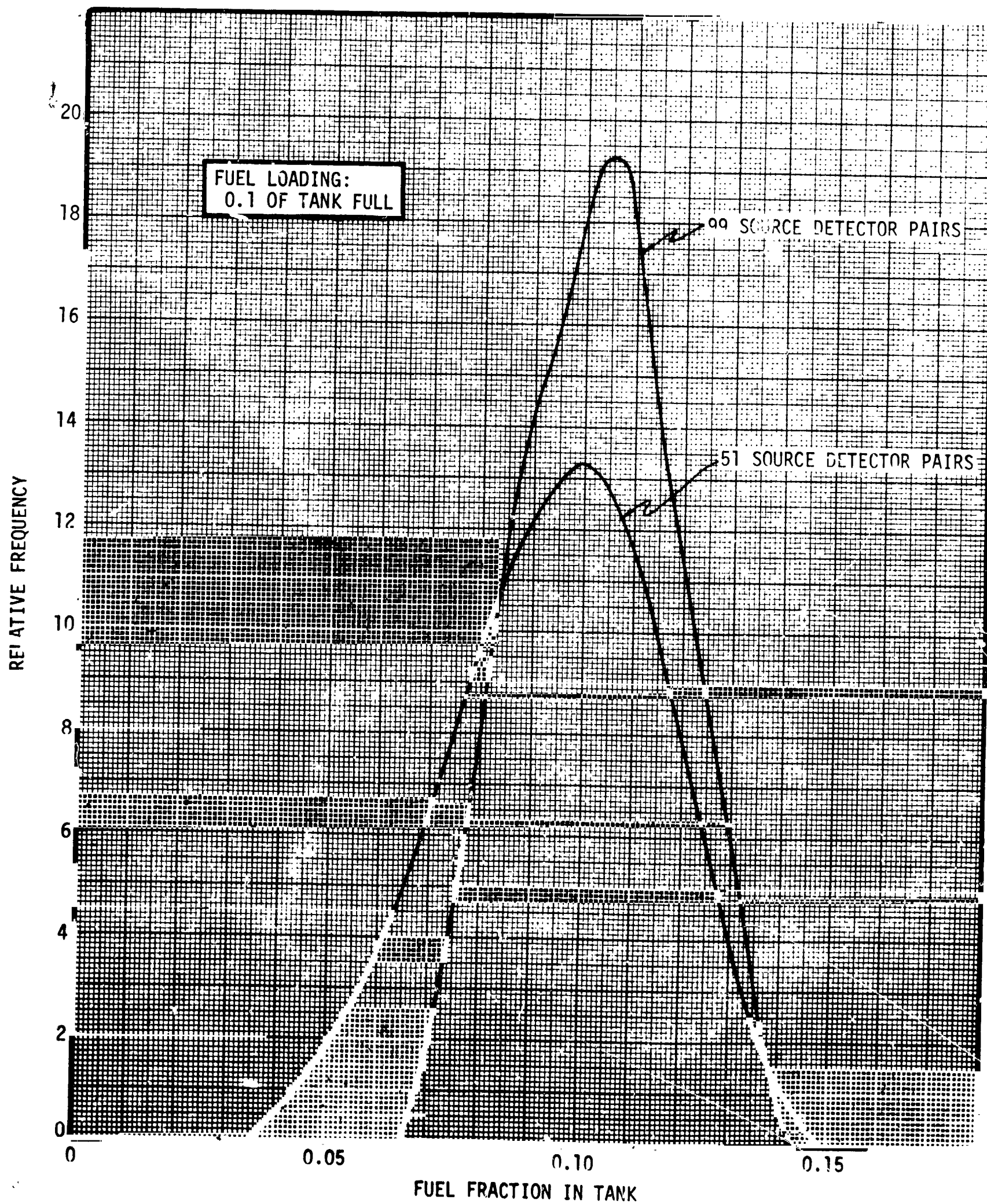


FIGURE 8. ERROR DISTRIBUTION FUNCTIONS FOR 51 AND 99 SOURCE DETECTOR PAIRS

A significant problem identified in the use of a RIGS system for gauging LOX is the requirement of keeping liquid away from the follower diaphragm. An isolation diaphragm is required. The design of the diaphragm requires that the area of the isolation diaphragm be at least ten times that of the weighted diaphragm and that the material be compliant and compatible with LOX. Materials suitable for use as an isolation diaphragm were considered.

TRW is presently engaged in a "Seal Material Development Program" under contract NAS 9-10481.* The objective of this program has been to develop compliant seal materials for oxygen-hydrogen propulsion systems.

The glass transition temperature for all known polymers is above 150°K, however, once below this temperature, the general physical properties of the material do not change rapidly with decreasing temperature. Since the temperature domain (90°K) in which the diaphragm must work is not significantly below the compliance limit imposed by existing polymers, evaluation of certain candidate materials has been undertaken.

Neat polymers (no fillers or additives are used, i.e., teflon, HYSTL, AF-E-124D) have good sealing characteristics and high resistance to brittle failure. Hydrocarbon and silicone elastomers meet the requirement for flexibility.

A fluoroelastomer, AF-E-124D, has emerged from the referenced program as a significantly superior material for cryogenic applications. The evaluation recently completed indicates that AF-E-124D shows no permanent deformation at elevated temperatures, which must be considered in the RIGS application since the system must experience long periods of storage without propellant under elevated temperature conditions. A small sample of the material was immersed in liquid nitrogen and observed to maintain a degree of resilience. A laboratory test for flexure of this elastomer is being outlined.

The measurement of a representative temperature of the ullage vapor is a significant requirement for RIGS. The gas gamma must be determined from this temperature requirement.

*"Seal Material Development Program" Phase 1, Final Report
14771-6001-P0-00, 31 December 1970.

3.2.3 Ultrasonic Gauging

Recent developments at National Reactor Testing Station have demonstrated the ability of an ultrasonic technique to detect liquid quantity, independent of location.* This device was designed to measure a steam/water ratio in the experiments being conducted to determine the consequences of a reactor loss of coolant accident.

Since average temperature is a stringent requirement in any of the fuel quantity systems, further consideration of the ultrasonic technique has been undertaken. The ultrasonic system has the capability of measuring both temperature and mass with a single transducer. This technique is illustrated in Figure 9. By pulsing the transmitter coil and measuring the time of arrival and amplitude of the signal at the receiver coil, both temperature and density can be obtained. The transit time of the pulse is a measure of the tube temperature, and the amplitude of the pulse is a measure of the density of the material in contact with the tube. By placing a series of receiver coils along a given tube, as shown in Figure 10, a scanning system can be constructed which will determine the two parameters.

The characteristics of an ultrasonic shear wave in cryogenic environments have been investigated. The speed of sound in an elastic medium is:

$$C_l = \sqrt{(\lambda + 2\mu)/\rho} \quad 6)$$

$$C_t = \sqrt{\mu/\rho} \quad 7)$$

Where C_l = longitudinal (compressional) speed of sound

C_t = transverse (shear) speed of sound

ρ = density

λ & μ = Lamé constants

The Lamé constants are:

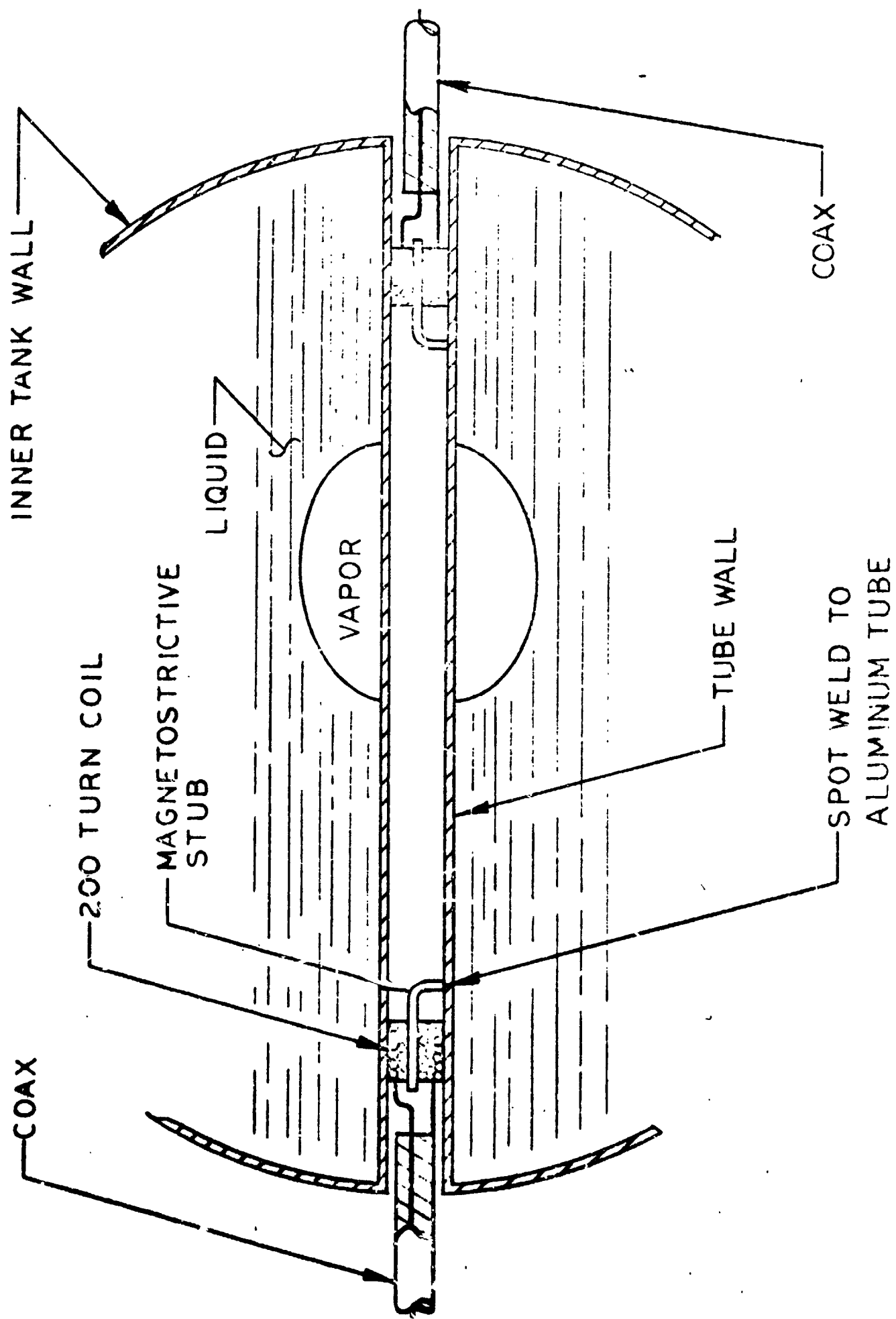
$$\lambda = \frac{Y \nu}{(1 + \nu)(1 - 2\nu)} \quad 8)$$

$$\mu = \frac{Y}{2(1 + \nu)} \quad 9)$$

Where ν = Poisson's ratio

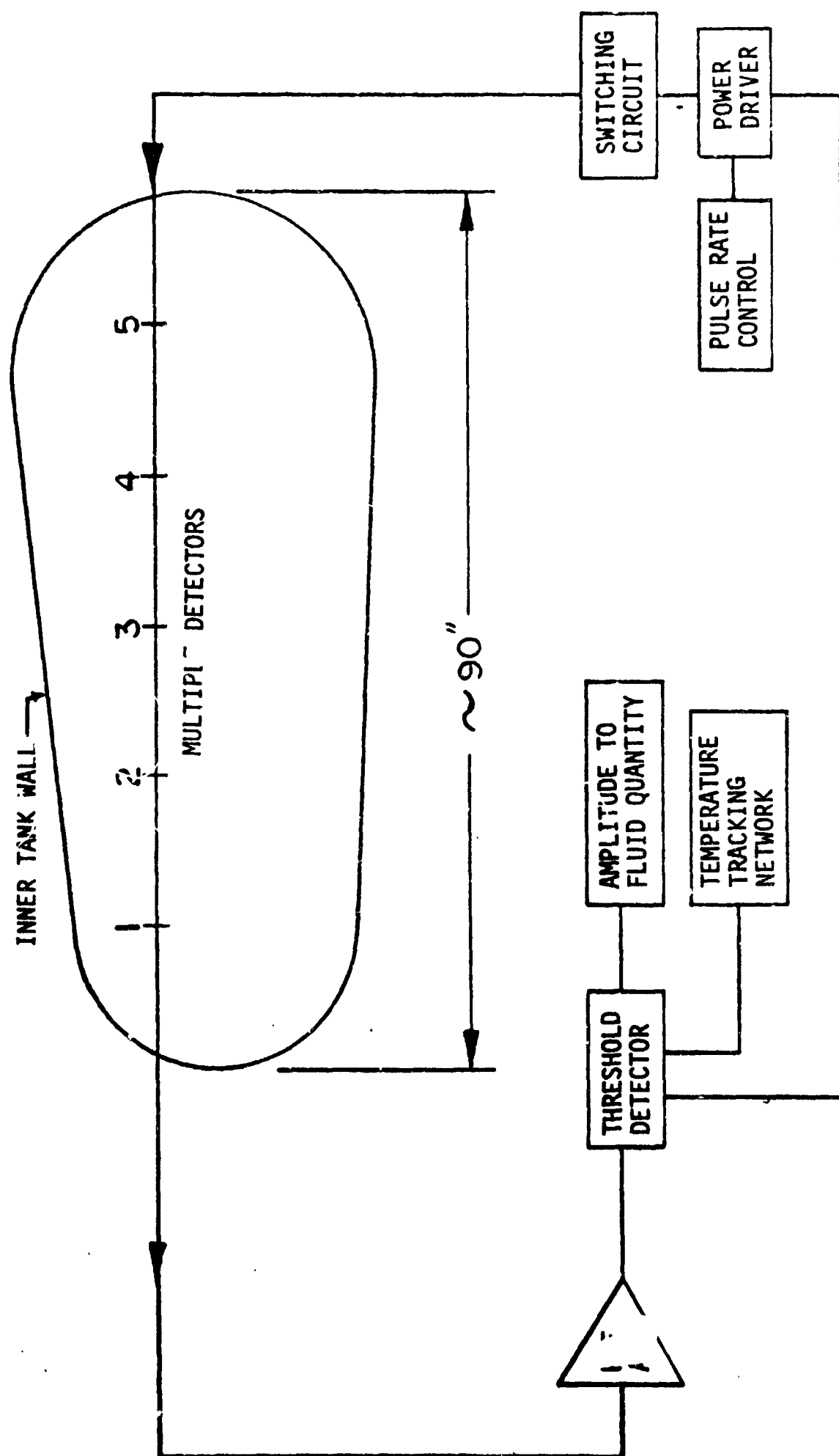
Y = Modulus of elasticity

*Arave, A. E. "An Ultrasonic Liquid Level Detector Using Shear Wave Attenuation in a Bar." IN-1442, Instruments, TID-4500, Nov. 1970.



BASIC ULTRASONIC LIQUID QUANTITY GAUGE

FIGURE 9



MULTIPLE DETECTOR ULTRASONIC GAUGE

FIGURE 10

Since density is a function of temperature the speed of sound can be plotted as a function of temperature and is given as:

$$\rho(t) = \rho_0 / (1 + \alpha(t))^3$$

$\rho(t)$ = density at temperature t

ρ_0 = density at 0°C (reference)

$\alpha(t)$ = linear expansion coefficient at temperature t .

The handbook values were used to compute the shear wave velocities in typical propellant tank materials (aluminum 2014-T6*) and are presented in Figure 11. The shear wave is used as the measured parameter since the geometry under consideration optimizes that mode of transmission. The fundamental relationship is that the compressional wave velocity is approximately twice the shear wave velocity and is displaced in time by a constant. Since the shear wave is the significant measurement, the electronic detection system is designed to see only the time of arrival of the shear wave.

The fundamental characteristics of ultrasonic waves can be utilized to obtain the desired measurement if care is exercised in detecting the correct wave form. Time of arrival and amplitude of the received signal are measurement of the temperature and density of the media through which the signal is passing.

An outline of a laboratory test to demonstrate the ultrasonic gauge performance in liquid nitrogen has been submitted to MSFC for approval.

3.3 Destratification by Spraying

Various concepts being considered to preferentially position the liquid have been reviewed. This has included acoustical pumping, and a review of capillary screening designs. The cryogenics mixing studies reported by General Dynamics have been reviewed.* The preferential positioning of the liquid enhances any zero-g measurement.

The conclusions reached have been that a sprinkler concept of positioning the liquid merits field testing. The design of the system is not trivial, and care must be exercised in selection of the nozzle, the control valve, and the driving pump.

A program outline for a preliminary test in zero-g has been submitted to MSFC by TRW. The system design will avoid ullage disruption by controlling the vapor consistency and avoiding a significant pressure buildup.

*FZA-450-1 Study of Cryogenic Fluid Mixing Techniques - Final Report 15 Sept. 1970.

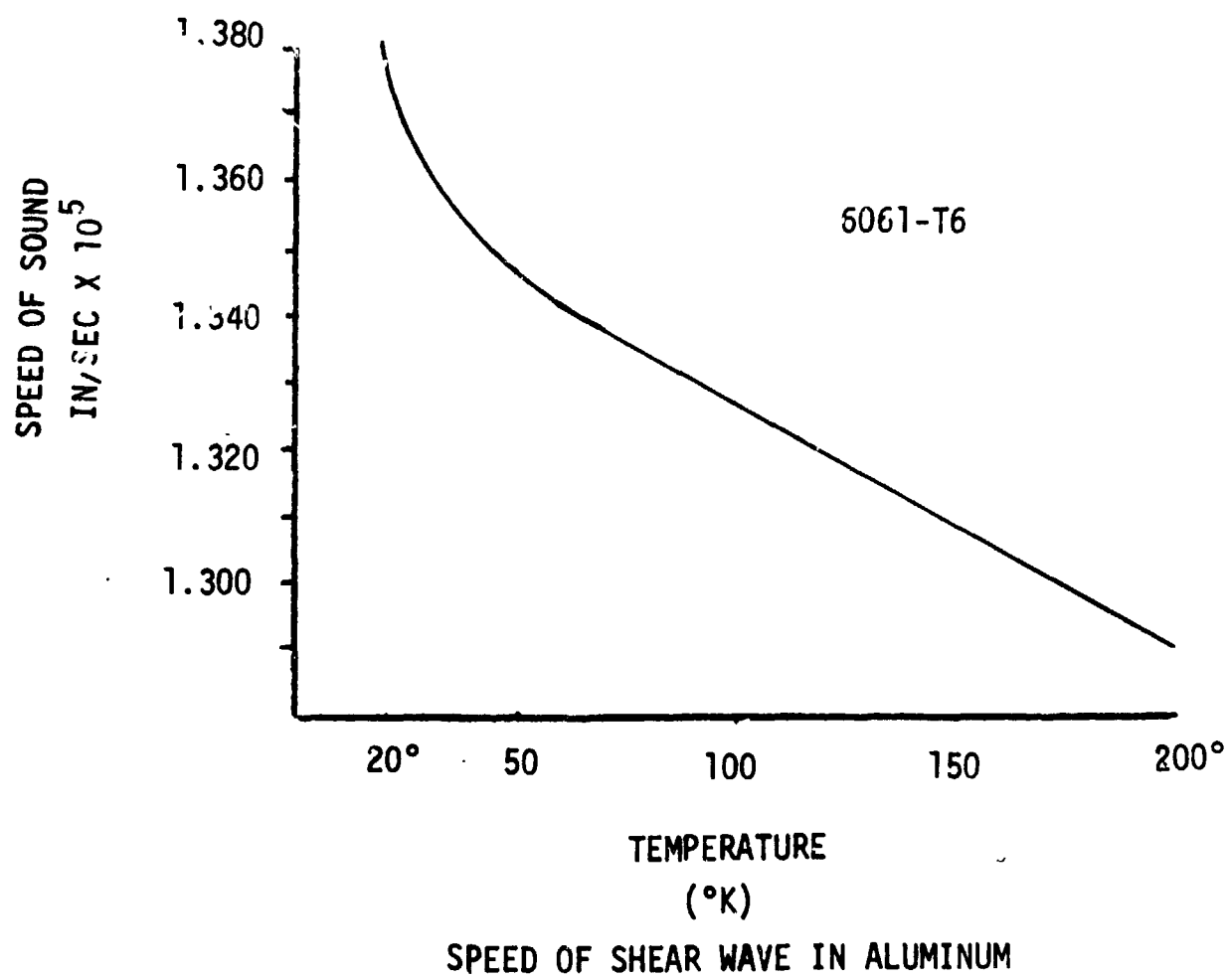


FIGURE 11

4.0 SUMMARY AND CONCLUSIONS

The objective of this program have been to identify key problem areas in various systems being considered for zero-g propellant quantity measurements.

The systems considered in greatest detail have been the Resonant Infrasonic Gauge and the Nuclear Gauging System. Key problems identified in these two concepts have been the requirement for an accurate average temperature measurement of the vapor. In addition, structural requirements have been identified for RIGS. A compliant driver diaphragm for cryogenic performance and an isolation diaphragm to keep liquid away from the resonating element are necessary.

The error analysis presented for the nuclear system indicated that the source-detector pairs originally predicted for a given tank geometry were optimistic. The analysis is valid for any system requiring detection of a discrete or segmented volume. Since a nuclear system is being developed on another contract, the performance on this program will be limited to observation and evaluation of the system being developed.

A new concept utilizing ultrasonics has been studied. Due to the significance of the approach, i.e., simplicity and ruggedness of basic hardware, laboratory tests are strongly recommended.

5.0 CONTINUING ACTIVITY

Laboratory test plans have been generated and hardware required for basic tests acquired to test the elastomer required for RIGS and the basic concept identified in the ultrasonic technique system.

Tests will be conducted on elastomer compliance in liquid nitrogen. A basic ultrasonic system will be tested in liquid nitrogen.

An engineering conference at MSFC will be scheduled during the next quarter, and final evaluation of the various systems made.

APPENDIX A

CONFIDENCE INTERVALS FOR THE ABSOLUTE ERROR VALUES

The following definitions describe a confidence interval:

- 1) The limits which will contain a parameter with a probability of $x\%$ are called the $x\%$ confidence limits for the parameter
- 2) The interval between the confidence limits is called the confidence interval.

Hence, if it is assumed that the distribution of the standard deviations (absolute error values) is normal (true for large number of samples), the confidence limits may be found from equation A1) ⁽¹⁾.

$$\frac{\bar{\sigma} - \sigma}{\sigma_s} = \pm Z_c(x) \quad A1)$$

where: $\bar{\sigma}$ = Confidence limits
 σ = Calculated standard deviation
 σ_s = Standard deviation of the standard deviation distribution
 $Z_c(x)$ = Confidence coefficient for $x\%$ confidence

The $Z_c(x)$ value corresponds to the number of standard deviations required to contain $x\%$ of the area under a normal curve. The σ_s value may be found from equation A2) which is valid for large number of samples only.

$$\sigma_s = \sigma' / \sqrt{2n} \quad A2)$$

where: σ_s = Standard deviation of the standard deviation distribution
 σ' = The true standard deviation of the total population
 n = Number of samples

It is assumed here that, σ' , the true standard deviation of the total population may be fairly well approximated by the calculated standard deviation σ . Hence, the confidence limits are given by equation A3):

$$\bar{\sigma}_1 = \sigma + Z_c \sigma_s$$

A3)

$$\bar{\sigma}_2 = \sigma - Z_c \sigma_s$$

where: $\bar{\sigma}_1$ = upper limit of the 95% confidence interval
 $\bar{\sigma}_2$ = lower limit of the 95% confidence interval

or by equation A4):

$$\bar{\sigma}_1 = \sigma + Z_c \sigma / \sqrt{2n}$$

A4)

$$\bar{\sigma}_2 = \sigma - Z_c \sigma / \sqrt{2n}$$

For the 95% confidence interval and 400 trials equation A4) becomes:

$$\bar{\sigma}_1 = \sigma + 0.08 \sigma$$

A5)

$$\bar{\sigma}_2 = \sigma - 0.08 \sigma$$

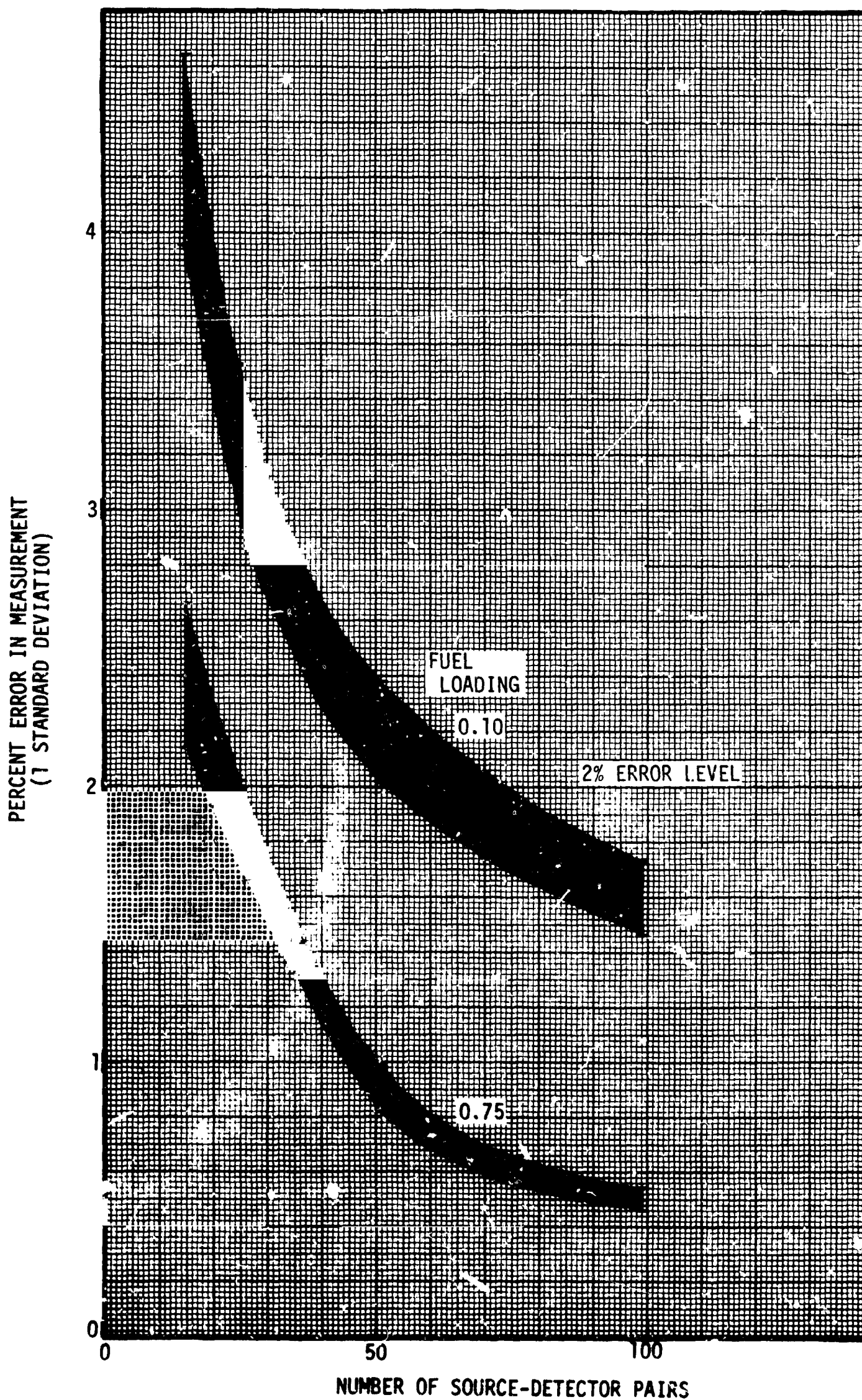


FIGURE A-1 95% CONFIDENCE BANDS FOR THE PERCENT ERROR VALUES (SIMPSON'S RULE INTEGRATION).

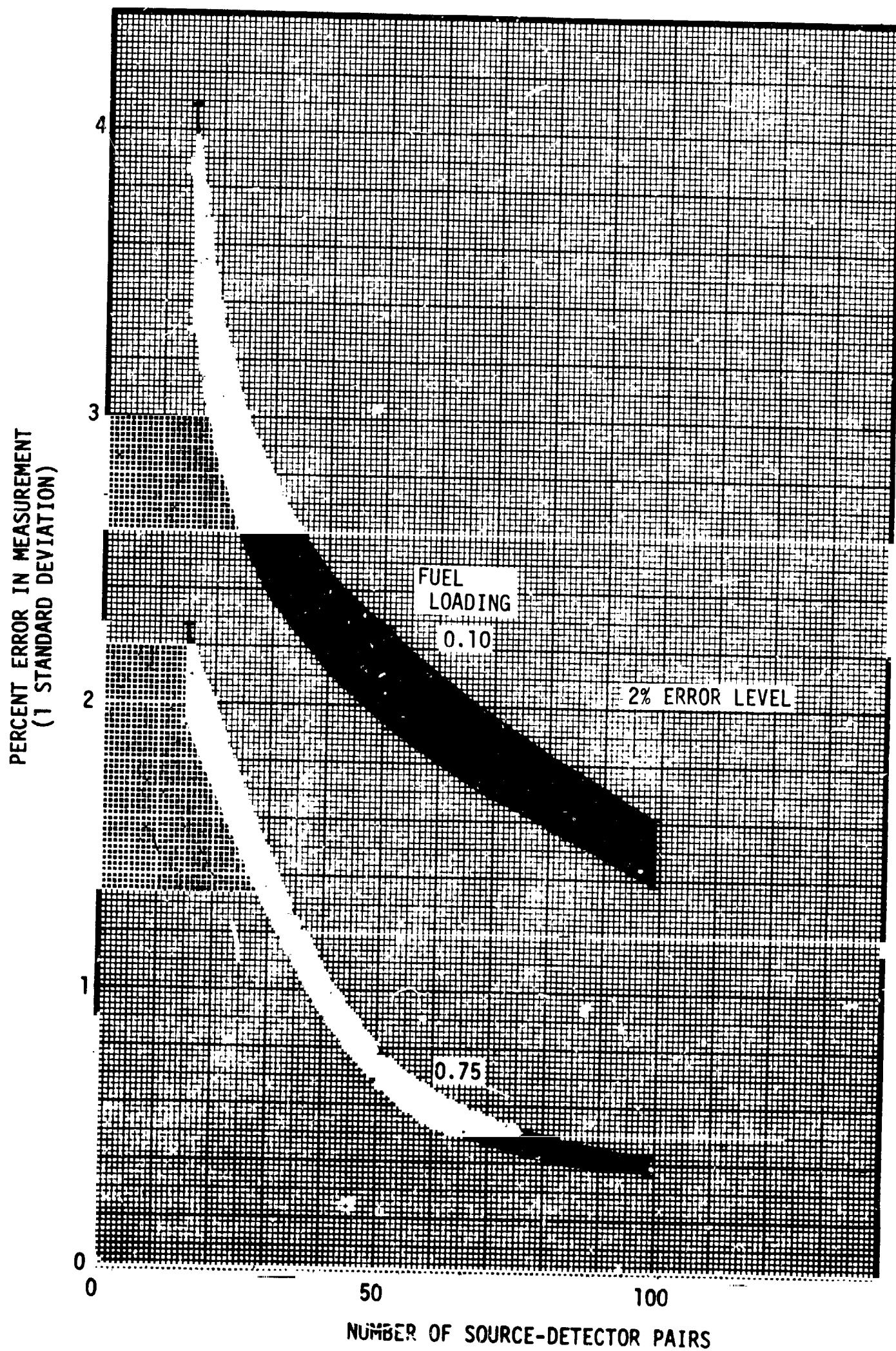
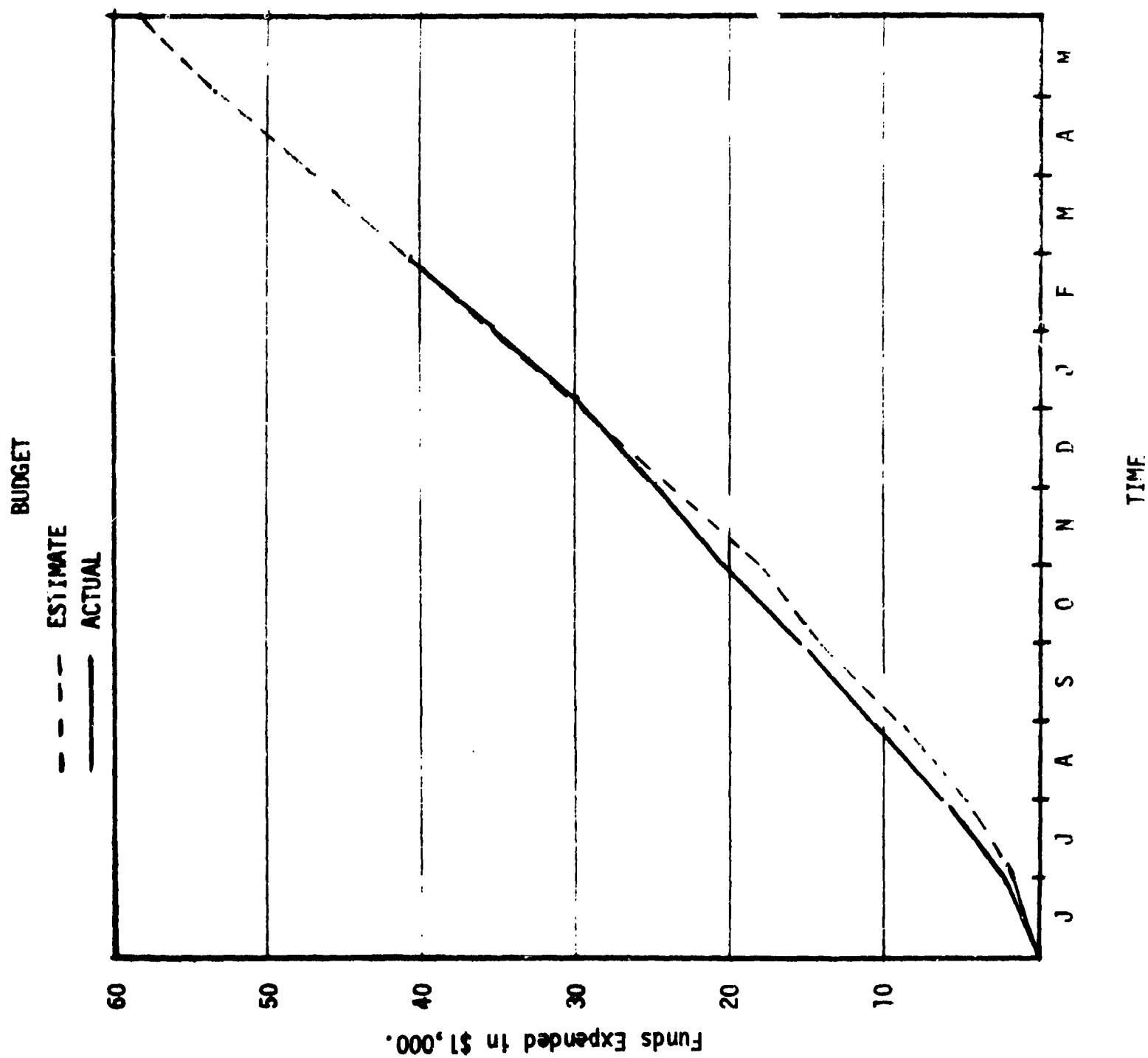


FIGURE A-2 95% CONFIDENCE BANDS FOR THE PERCENT ERROR VALUES (AREA WEIGHTING INTEGRATION)



00 PROGRAM EXPENDITURES
FIGURE B-1